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WATER CONDUCTION FROM SHALLOW WATER TABLES[1, 2]

ROSS E. MOORE[3]

INTRODUCTION

THE PHENOMENON of the flow of liquids through porous mediums without the application of external force and without complete filling of the pores of the solid with liquid, has long been recognized and studied. It was early recognized that the forces involved are those of adhesion and cohesion, the same as those responsible for the action of liquids in capillary tubes. The term "capillarity" (*6, 17*)[4] has thus come to apply to the flow of liquids through porous mediums.

Many analyses (*28–31*) have been made for the purpose of evaluating the capillary forces acting in three-phase systems, such as is the case in moist soil, consisting of solid, liquid, and gas, by assuming spherical solid particles of uniform size and sequence of packing arrangement. While this assumption has presented concepts of value in comprehending the mechanism involved in capillary flow, the size and configuration of the solid and liquid phases are very complex in even the most idealized systems, and become indeterminate when applied to natural bodies such as soil.

The capillary potential concept, introduced by Buckingham (*6*) in 1907, assumed a capillary force field generated by the attraction of moist soil for water. He defined a capillary potential, the gradient of which is equal in magnitude to the capillary force. The introduction of the potential function gave rise to the study of soil-moisture as a dynamic system; but this method received no added impetus until 1922, when Gardner (*9*) and others showed that the capillary potential of Buckingham may be

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[2] Abridged from a thesis submitted in partial fulfillment of the requirements for the degree of doctor of philosophy.

[3] Instructor in Soil Technology and Junior Soil Technologist in the Experiment Station.

[4] Italic figures in parentheses refer to "Literature Cited" at end of this paper.

considered as a pressure potential due to the differential pressures on either side of the liquid-gas interface in the menisci of the water films. They further showed it to be directly measurable, over a certain range of potential, by measuring the negative hydrostatic pressures within the water films of soil moisture. The instrument used for these direct measurements was called a capillary potentiometer, but is now called a tensiometer (*19*), and consists of a porous absorbing element, an adaptation of the Livingston Auto Irrigator, to which a manometer is attached. When the capillary potentiometer was filled with water and the porous absorbing element was embedded in the moist soil whose capillary potential was to be measured, water transfer took place between the porous element and the soil until, at equilibrium, the pressure of the water inside the potentiometer was equal to the pressure in the soil-moisture films. This pressure was read directly on the manometer.

In the application of the dynamic concept to soil moisture studies, the velocity of flow of water through the soil is considered to be proportional to the total water-moving force. A conductivity factor, variously called capillary conductivity, capillary transmission constant, conductivity, and permeability, has been used to express this proportionality (*3, 7, 8, 10, 16*). The term "permeability" is adopted in this paper.

Many data on the permeability of soils in saturated flow or, with the pore spaces entirely filled with water, are available in papers of the U. S. Geological Survey, the American Geophysical Union, and in engineering papers. Slichter (*24*) made theoretical calculations for the flow of underground water under pressure, in which it was assumed that the velocity of flow was proportional to the pressure gradient. There are relatively few published data on soil permeability in unsaturated flow, however. Such data as have been reported were derived from experimental results on relatively small quantities of soil through which flow was induced by artificially maintaining differential pressures in the moisture films on either side of the sample. Richards (*17, 18, 20*) has published data on three soils, including capillary potential as a function of water content, permeability as a function of water content and capillary potential, and permeability of a peat soil as a function of capillary potential.

The evaluation of the movement of water through unsaturated soil is important in many practical problems, such as: the drainage of land, of road subgrades, and of all structural foundations and pavements laid on the ground; the contribution of a water table to the water supply of plants; the loss of water from a soil surface by evaporation; and the upward translocation and concentration of soluble salts in the soil.

This paper reports pressure potential and saturated and unsaturated permeability data, using six California soils. The rate of water flow required to maintain shallow water tables in cylindrical soil columns 8 inches in diameter, was measured in graduated supply burettes. Unsaturated flow was induced naturally; the water rose from the water table to the surface of the soil columns by capillarity, and was evaporated from the surface. Tensiometers were spaced at regular intervals on the vertical axis of the soil columns, and the pressure potential values were read directly on these instruments. When the rate of water uptake and the pressure potentials throughout a soil column became steady, that column was said to be at steady state. Its moisture distribution was then determined by sampling, and its saturated and unsaturated permeabilities at various pressure potentials were determined from the velocity of flow and the total potential gradient.

PROCEDURE

The moisture studies reported herein were carried out in a room in a light frame building of the University of California at Berkeley. The room was 8×16 feet, and 12 feet high, with a reinforced concrete floor laid on the ground. The walls were of tongue-and-groove pine sheathing on 2×4 inch studs spaced at 2-foot centers, the naked studs being on the room side. After beginning this experiment, the walls and ceiling were lined with celotex wallboard which was nailed to the studs.

The room was heated by two batteries of electrical heating elements, one battery placed at either end of the room about 4 feet from the end walls and 6 feet from the floor. Heat distribution was effected by four electric fans, so placed as to give maximum air turbulence as well as general air circulation to all parts of the room.

The heating elements had two circuits, one continuous and one intermittent. The intermittent circuit was opened and closed by a thermal regulator through a relay. Temperature at the thermal regulator was set at 30° C, and controlled to about $\pm$ 0.02°. Temperature along the sides of the room and near the floor could not be held to this narrow range due to heat loss through the rather poorly insulated walls. The soil columns, which were set in a row close to a wall, normally held to a temperature range of 0.02° C, except during periods of abnormal change in the atmospheric temperature outside the room.

Six soils were used, ranging in texture from sand to clay (table 1). All except one, the Oakley sand, were of the Yolo series. The air-dry soils were prepared for filling the cans by breaking them down to pass a 3-mm screen.

The soil cans were of galvanized iron, cylindrical, 8 inches in diameter and 3 to 4 feet high (fig. 1), and were fitted with a wire-screen diaphragm soldered 2 inches above their bases to provide support for the soil columns. A water inlet tube, ¼ inch in diameter, was soldered 1 inch above the bottom of each can. Each can was punched with ⅝-inch holes in four vertical rows, one row at each quarter point on the can's circumference. The vertical distance between holes in the row and the elevation of each row, were arranged to give a hole for each inch of can height. Before a can was filled with soil the holes were closed with patches of celluloid cemented to the outside. When the wetting front in the soil column reached a hole, the celluloid patch was removed, the soil sampled for moisture content, and the hole reclosed with a rubber stopper.

TABLE 1

Mechanical Analysis and Moisture Equivalents of the Soils Used

Separates	Oakley sand	Yolo sand	Yolo fine sandy loam	Yolo clay loam	Yolo light clay	Yolo clay
Fine gravel	0.2	2.9	0.1	0.1	....	....
Coarse sand	9.9	16.4	0.3	0.5	0.1	0.2
Medium sand	15.3	25.8	0.5	0.6	0.4	0.3
Fine sand	45.1	41.8	18.9	5.3	7.2	3.0
Very fine sand	20.4	6.0	31.0	21.0	16.1	8.1
Total sand	90.9	92.9	50.8	27.5	23.8	11.6
Total silt (by difference)	3.5	3.3	31.5	46.0	45.0	46.5
Total clay	5.6	3.8	17.7	26.5	31.2	41.9
Clay <2 micron	4.6	3.2	12.8	17.2	23.2	33.1
Clay <1 micron	4.0	2.9	9.4	13.5	17.4	26.5
Moisture equivalent	4.3	3.5	18.1	22.5	25.0	26.3

The procedure in filling the can with soil was similar to the tremie method for placing concrete under water (*36*). A strong fiber tube, 4 inches in outside diameter, and 4 feet long, originally made for the packing and shipment of glass tubing, was used as a tremie.

The tremie tube, surmounted by a funnel, was placed upright in the soil can. One man kept the funnel and tremie full of soil and a second man operated the tremie, partly supported its weight, kept it vertical, and moved it with a rotary motion so that the tube described a circle, the diameter of which was equal to the diameter of the soil can. The bottom of the tube, resting lightly on the soil, passed over the entire area of the soil column at each revolution, and thus maintained a level and regular surface. Approximately eight revolutions of the tremie were required per inch of depth of soil column laid down.

The entire system, can, tremie, and soil, was weighed at intervals of approximately 4 inches in the soil-column height. For the height of soil

at each 4-inch stage the mean of eight to ten measurements was taken; these measurements were made from the top of the can with a meter stick which was dropped vertically onto the soil through a distance of ap-

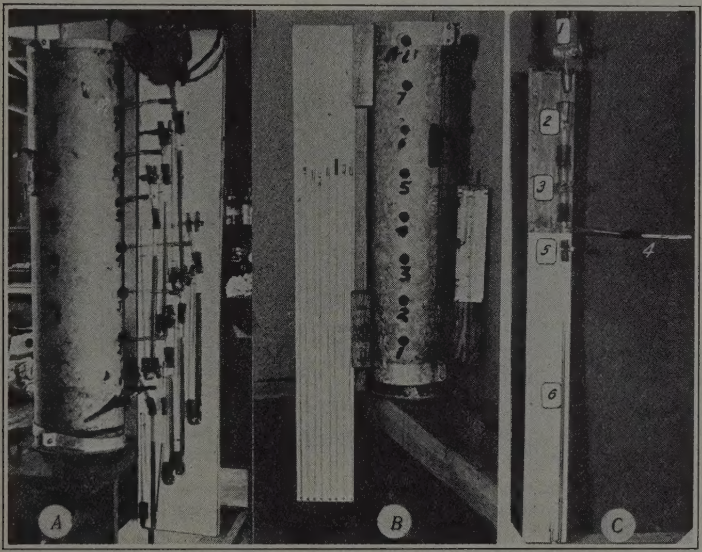


Fig. 1.—Soil cans with tensiometers installed.

A, Can with mercury tensiometers, showing the method of attaching the manometer panel and the installation of the tensiometers. The instrument at the top of the panel is a vibrator. The lowest tensiometer has been removed from the soil to show the cup (absorbing element).

B, Can with water tensiometers installed. Eight tensiometers with water manometers are mounted on the left panel. The tensiometers enter the soil column back of the panel. Two open water manometers used for positive potentials only are mounted on the small panel at the right.

C, Assembly of the tensiometer with a mercury manometer. This assembly was used for testing tensiometer cups and is the same as the tensiometers installed in the soil columns except that the stopcock, *3*, was replaced by a screw clamp. Details are as follows: *1*, A three-way stopcock sealed to a male standard taper ground glass connection. The two rubber tubing lines supply vacuum and water at atmospheric pressure. *2*, Female standard taper ground glass connection. *3*, Two-way stopcock. *4*, Porous fired-clay tensiometer cup. *5*, Screw clamp. *6*, Capillary staff of mercury manometer.

proximately 1 inch. The net weight of soil in the can was later corrected for air-dry water content.

Too few weighings were made on an individual soil column to allow a statistical calculation of variation in apparent density for a single column. A mean apparent density was calculated for each column, and

the densities for each stage of filling were expressed as percentages of that mean. These percentages were collected for all the soil columns, analyzed statistically, and a single standard deviation was calculated and expressed as per cent variation from the mean apparent density. This single value was assumed to represent the standard deviation in apparent density for all the soil columns (table 2).

Water at constant pressure was supplied to the base of the columns by water supply units (fig. 2), carried upward through the soil by capillarity, and removed from the soil surface by evaporation. The rate at which water was taken up by the soil was measured in the graduated supply burettes of the water supply units, and the upward advance of the wetted front was observed through the celluloid-covered holes in the sides of the cans.

TABLE 2

CHARACTERISTICS OF THE SOIL COLUMNS

Soil type and can number	Length of soil column, centimeters	Cross section, square centimeters	Wetting time, days	Drying time, days	Mean apparent density	Standard deviation of apparent density	Standard deviation of mean apparent density	Per cent pore space	Per cent water at saturation by weight, oven-dry basis
Oakley sand, 3	117	314	312	9	1.48	0.042	0.004	43.3	29.2
Yolo sand, 13	84	322	108	5	1.49	.042	.005	43.0	28.8
Yolo fine sandy loam, 1	117	314	286	72	1.28	.036	.004	51.0	39.8
Yolo fine sandy loam, 17	84	322	21	7	1.24	.035	.004	52.5	42.3
Yolo fine sandy loam, 20	84	323	64	..	1.25	.035	.004	52.1	41.6
Yolo clay loam, 14	84	321	98	14	1.34	.038	.004	48.6	36.2
Yolo clay loam, 19	84	322	25	3	1.28	.036	.004	51.0	39.8
Yolo light clay, 2	117	314	310	34	1.32	.037	.004	49.5	37.5
Yolo light clay, 18	84	320	25	..	1.29	.036	.004	50.5	39.1
Yolo light clay, 20	84	323	29	3	1.27	.036	.004	51.3	40.4
Yolo clay, 15	84	322	89	13	1.28	.036	.004	51.0	39.8
Yolo clay, 16	84	312	37	..	1.22	0.034	0.004	53.2	43.5

Tensiometers (*19*), consisting of porous fired clay absorbing elements connected to vacuum gauges of the manometer type, were placed in the soil columns one above the other at intervals of 10 centimeters (fig. 1). A transfer of water takes place between the soil and the absorbing element until, at equilibrium, the pressure of the water in the absorbing element is equal to that in the moisture films of the soil. This pressure is calculated from the height of mercury or other manometer liquid used in the vacuum gauge.

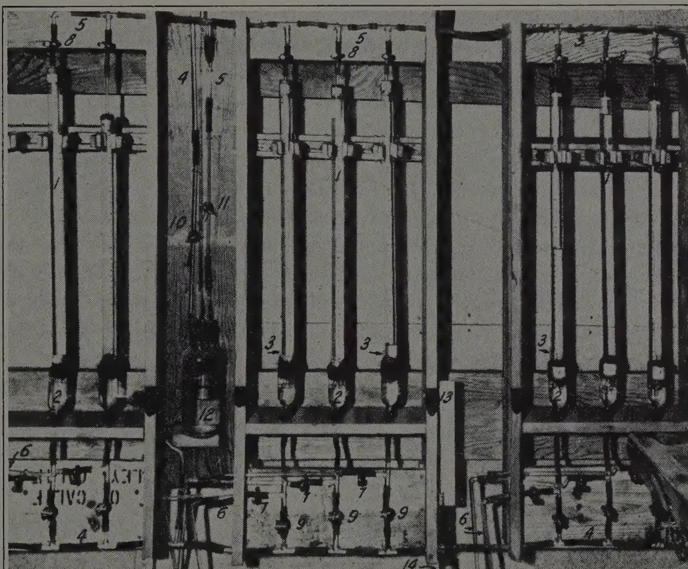


Fig. 2.—Battery of eight water supply units. The details are: *1,* Graduated burettes; *2,* constant-level reservoirs; *3,* air vents; *4,* water supply line from 20-liter supply bottle; *5,* suction line from 20-liter supply bottle; *6,* water lines from constant-level reservoirs to the soil columns; *7,* screw clamp cut-offs on water lines to the soil columns; *8,* screw clamp cut-offs on suction line; *9,* screw clamp cut-offs on water line from the 20-liter supply bottle; *10,* two-way stopcock on water line from 20-liter supply bottle; *11,* two-way stopcock on suction line from 20-liter supply bottle; *12,* water trap in the suction line; *13,* graduated staff tube for measurement of the outflow required to make burette, 1, "gurgle"; *14,* water outlet, used to drain water out of the system.

A burette was filled by closing *7* and opening *8* and *9*. By manipulating *10* and *11,* water flowed through *4* into the constant level reservoir, *2,* and was drawn up into the burette, *1,* by suction on the line, *5*. In operation, with water being supplied to the soil columns, *8* and *9* were closed and *7* was open. Two tubes ran through a 2-hole stopper from *1* into *2*. The lower ends of these tubes were at different elevations so that one tube was continuously immersed in water in *2*, and the end of the other controlled the variation in the elevation of the water level in *2*. When the water level dropped in *2*, air was admitted into *1* through the higher tube and water flowed from *1* to *2* through the other tube, raising the water level in *2* until the end of the higher tube was again immersed and the air supply to the burette was cut off. This cycle was called a "gurgle." At each "gurgle" about 6 cc of water flowed from *1* to *2*, causing a momentary rise of the water surface in *2* of about 0.5 cm. This was sufficient to cause a fluctuation of about 0.4 mm in the water table in the soil column, therefore a water table maintained by this method was relatively constant.

Both negative and positive pressure potentials of the water in the soil columns were measured with tensiometers. Open water manometers of the staff-gauge type were also used in some of the columns for the measurement of positive potentials. For the purpose of these measurements, the pressure potential of the atmosphere was arbitrarily taken as zero.

When the flow of water through the soil columns attained steady state, as indicated by a constant rate of water uptake and steady pressure potentials at each point of measurement, the soil was sampled for moisture content. The steady-state potentials and moisture contents were tabulated and represented graphically. The graphed data (figs. 9–13) include two wetting curves for each soil column:

(1) Moisture content as a function of elevation above the base of the soil,

$$P_w = f(H).$$

(2) Pressure potential as a function of elevation above the base of the soil,

$$\psi = F(H),$$

where: P_w is the per cent water in the soil on the oven-dry basis determined by drying for 24 hours at 105° C. H is the elevation in centimeters above the base of the soil column. ψ is the pressure potential in gram-centimeters per gram (in this paper abbreviated as gm–cm/gm).

After pressure potential and moisture content data had been collected for the soils wetting up, the water supply was removed and a soil-air interface was maintained at the base of the soil columns. During drying, the moisture density throughout the soil columns was reduced by continued evaporation from the surface and by downward flow of water. When the rate of moisture density change and pressure potential change had reached low values at all points in the soil columns, the soils were again sampled for moisture content and pressure potential readings were taken. These data were also tabulated and graphed as $P_w = f(H)$ and $\psi = F(H)$, drying.

The collection, tabulation, and graphical representation of all primary experimental data were included in the procedure outlined above. Later analysis of the primary data includes, first, an examination of the manner in which the pressure potential of a soil is affected by its moisture content, $\psi = f(P_w)$, and, second, an examination of the manner in which the soil permeability is affected by its pressure potential $K = F(\psi)$.

PRIMARY EXPERIMENTAL DATA

In this section are presented the quantitative experimental data discussed in the following order:

1. Mechanical analysis and moisture equivalent of the soils (table 1), and such characteristics of the soil columns as type, apparent density, and per cent pore space (table 2).

2. The manner in which pressure potentials and rate of water uptake vary with time during the wetting-up period (figs. 3 and 4).

3. The manner in which pressure potentials vary with time during the drying period (figs. 5 and 6).

4. The effect of temperature change on pressure potentials and the rate of water uptake in a soil column at steady state (fig. 8).

5. Pressure potentials and moisture distribution in soil columns at steady state (table 3 and figs. 9–13).

Soils Used.—The six soils used in the experiment were Oakley sand, Yolo sand, Yolo fine sandy loam, Yolo clay loam, Yolo light clay, and Yolo clay. All except the Yolo sand were collected from cultivated fields at depths of 2 to 8 inches. The Yolo sand is a stream-washed sand of the same origin as the Yolo soils and was collected in a commercial sand pit on the bank of Cache Creek.

The mechanical analysis of the soils was made by the pipette method using H_2O_2 and HCl pretreatment, and $Na_2C_2O_4$ as a dispersing agent.

The moisture equivalent determinations were made in duplicate on 30-gram samples of air-dry soil crushed to pass a 2-mm sieve. The samples weighed into the cups were moistened for 24 hours, drained for half an hour, and centrifuged for half an hour at a speed sufficient to develop a centrifugal force of 1,000 times gravity.

Mechanical analysis and moisture equivalent data are given in table 1. Numerical data descriptive of the soil in the columns are listed in table 2.

Pressure Potentials and Rate of Water Uptake as Functions of Time During the Wetting-Up Period.—The rate of water uptake as it decreased with time during approach to steady state was taken for all the soil columns. In figure 3 the log (rate of water uptake) is plotted as a function of the log (elapsed uptake time), $\log A = f(\log t)$, for Yolo clay, wetting. This curve is similar in form to those of all the soils studied in this experiment and conforms to observed data reported elsewhere (*35*) in the literature of which the example cited is only one of many.

An empirical equation for water uptake derived for a curve expressing

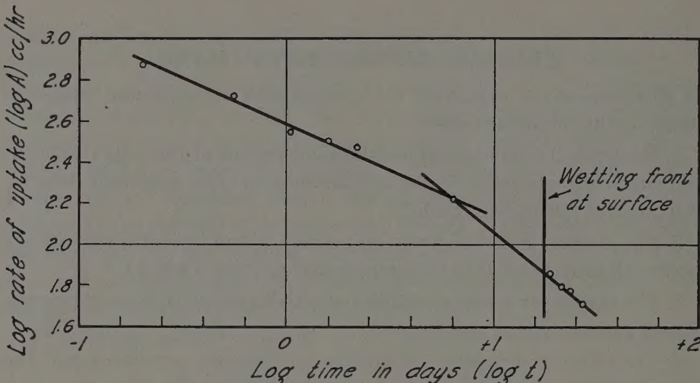


Fig. 3.—Rate of water uptake during approach to steady state, $\log A = f(\log t)$, for a column of Yolo clay wetting.

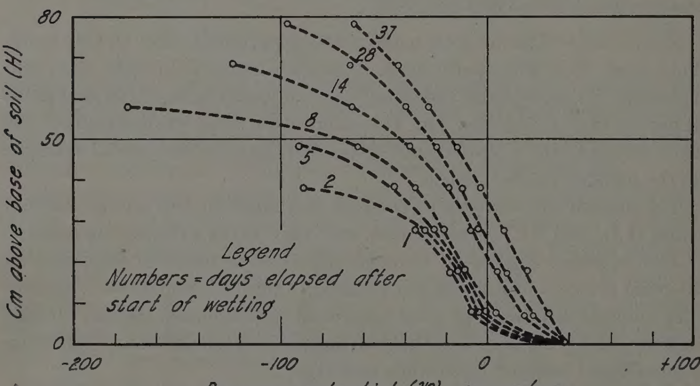


Fig. 4.—Distribution of pressure potential with the elevation above the base of the soil, $H = f(\psi)$ for a column of Yolo clay wetting.

$\log A = f(\log t)$ may be written in the form of an equation of a straight line,

$$\log A = -c(\log t) + \log K$$

or

$$A = kt^{-c}$$

where A is the rate of water uptake, t is the cumulative uptake time, and K and c are constants; c representing the slope or the rate of change of $\log A$ with $\log t$. The data for all the soil columns investigated conform to

the first equation, with the exception that the value of c changed abruptly before the surface of the soil at the top of the columns had become obviously wet. Referring to figure 3, the initial stage of advance of the wetting front includes on the time scale, from inception of wetting to a log t in days of approximately 0.8 or an elapsed time of 6.3 days. During this time interval the wetting front advanced through air-dry soil of relatively constant apparent density and packing arrangement from near

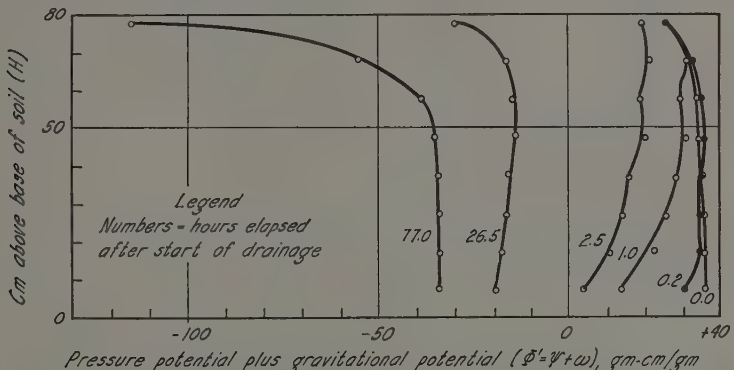


Fig. 5.—Distribution of the sum of the pressure and gravitational potentials with the elevation above the base of the soil, $H = f(\Phi')$ for a column of Yolo fine sandy loam drying.

the base of the soil column to within 1 or 2 mm of the surface. The 1 or 2 mm of soil at the top of the soil column was loosely packed and of lower apparent density than the remainder of the soil. Although the mulch was included in the length of the soil column, it is proposed that the contact between the mulch and the lower soil represented an irregular interface of discontinuity which was responsible for the change in the characteristic rate of water uptake.

A family of curves for Yolo clay representing the pressure potential distribution with elevation above the base of the soil at various cumulative wetting times is shown in figure 4, which, with the possible exception of the sands, is qualitatively characteristic of all the soils investigated during the wetting process. The potentials changed too rapidly in sands to be measured accurately.

Pressure Potential as a Function of Time During Drainage.—After upward flow in the soil columns had attained a steady state during the wetting process, the columns were drained by removing the water supply, and by maintaining a water-air interface at their bases. During drainage the change of pressure potential with time at various elevations

in the soil columns was recorded. The rate of change of pressure potential varied with texture, being greatest for sand and least for clay. The general character of the drainage curves, however, was similar for all the soils; therefore, data are presented for one soil only.

Figures 5 and 6 represent pressure potentials during drainage of a 3-foot column of Yolo fine sandy loam which had come to a steady state

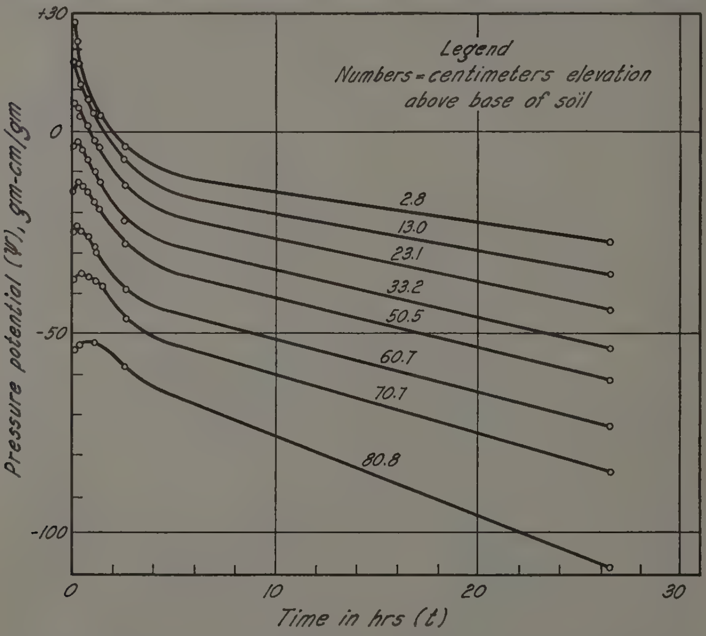


Fig. 6.—Distribution of the pressure potential at various elevations in the soil column with the time after drainage began, $\psi = f(t)$, in a column of Yolo fine sandy loam. Note the increase in pressure potentials in the unsaturated region of the column immediately after drainage began.

by wetting with a water pressure of 42 grams per square centimeter at the base of the soil column. The time when drainage began was arbitrarily taken as zero time, $t = 0$.

Figure 5 shows drainage curves for a column of Yolo fine sandy loam. For convenience in plotting, H is plotted as a function of Φ' which, however, should be considered the dependent variable, with the relation of Φ' to H expressed by the equation

$$\psi + \omega = \Phi' = f(H),$$

where H is the elevation above the base of the soil column in cm; ψ is the pressure potential in gm–cm/gm; ω is the gravitational potential in gm–cm/gm ($\omega = 0$ is arbitrarily taken at the elevation at which $\psi = 0$ when $t = 0$).

The total potential gradient had become approximately zero in the main body of the Yolo fine sandy loam column 60 hours after drainage began. This adjustment period required 24 hours and 96 hours in the Yolo sand and Yolo clay respectively.

Increases in pressure potentials immediately after drainage began were noted in all the cans at tensiometer positions above the water table (fig. 6). These increases indicated increases in the moisture density. Since even the highest tensiometer at an elevation of 80.8 cm above the base of the soil showed an increase in pressure potential, the water necessary must have been supplied from below.

A simple illustration taken from the case of a fully saturated single pore may explain the apparent anomaly of increasing pressure in the upper portion of a soil column induced by a sudden reduction in pressure at the base of the column. Figure 7 represents a capillary tube, the lower end of which had been dipped in water.

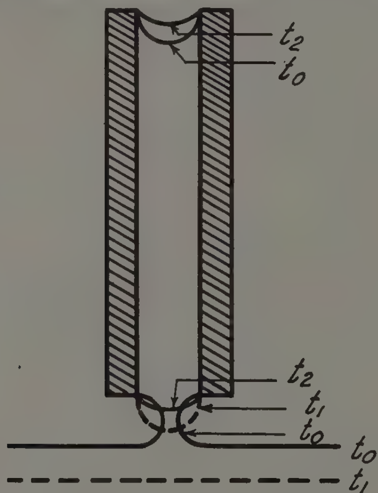
At time t_0 the water level has been lowered sufficiently to induce a temporarily reduced pressure potential about the lower tube opening, but at the same time to maintain a water connection between the free flat water surface and the capillary water in the tube. The pressure potential at the top of the capillary tube is ψ_0. Time t_0 represents the steady state condition in the soil columns at a position just above the surface of zero pressure potential.

At time t_1 the water level has been suddenly lowered. The water thread connecting the free flat water surface and the capillary water has broken. The water meniscus at the bottom of the capillary tube is convex to the air and the pressure immediately above the meniscus has increased from negative to positive.

At time t_2 the meniscus at the top of the capillary tube, which at t_0 was in equilibrium with a negative pressure at the base of the tube, has increased in radius of curvature to effect pressure equilibrium with the increased pressure at the base of the tube. An upward flow of water has taken place, and pressure potentials have increased throughout the capillary tube.

The discussion of the capillary tube in figure 7 deals with a fully saturated pore; whereas this experiment deals with a porous medium which is not saturated throughout its length, but is a three-phase system containing solid, liquid, and air. The energy involved, however, in the ad-

justment of water by capillarity in an unsaturated soil is due to the forces of gravity, adhesion, and cohesion, the same as are responsible for the movement of water in figure 7. The pressure potential changes induced by drainage of a soil column under the conditions of this experiment may be appropriately discussed by analogy to the capillary tube.



Time	Pressure in water under meniscus	
	Lower end	Upper end
t_0	−	−
t_1	+	
t_2	less +	less −

Fig. 7.—Diagrammatic illustration of the menisci and their changes in curvature during the withdrawal of a capillary tube from water.

The break in the continuity of the water system shown at time t_1 occurs in the large pores in the soil columns; the smaller moisture films in the soil which are capable of greater curvature remain continuous. Permeability in the moisture films of low curvature is relatively high; the pressure increase at the point of rupture of the large films postulated at a time corresponding to t_1 would result in an upward flow of water causing a temporary increase in pressure potentials.

General laboratory experiments on the distribution of water in soil over a water table have been conducted by setting soil tubes filled with

soil in vessels of water (*14, 15, 23*). In this type of experiment the soil rests on a porus support near the bottom of the soil tube and is in contact with water at atmospheric pressure. The elevation of the water in the outer vessel is kept constant, and it is assumed in these cases that the water table in the soil is at this elevation. After a duration of time, assumed to be sufficient for the establishment of a steady moisture distribution in the soil columns, the tubes are removed from the vessels of water and are sampled for moisture content. Such laboratory experiments have generally shown the highest moisture content to be some distance above the original water table. This distribution has been so universally observed in experiments that the experimental results have been interpreted as representing the actual moisture distribution in an undisturbed soil over a water table.

It should be observed here that removing the soil tubes from the vessels of water is not essentially different from the drainage technique reported in this paper. Consequently, the changes in pressure potentials during drainage which were observed in the experiment reported herein must have also taken place in the experiments cited above. These pressure potential changes (fig. 6) indicate that an upward flow of water takes place immediately after drainage begins, which flow may cause the highest moisture content, at the time the column is sampled, to occur at some distance above the original water table.

Effect of Temperature Variation on Pressure Potentials and Rate of Water Uptake.—The experiment was designed to study soil-moisture movement at constant temperature. Temperature variation in the soil was held within a range of 0.2° C except during four short periods during which a high positive correlation between increasing or decreasing temperature and certain observed features in the behavior of the soil-moisture system permits a statement of the qualitative effect of temperature variation on these features.

A drop in temperature always resulted in an increased rate of water intake and in lower pressure potentials throughout the columns in all the soils. A rise in temperature had the reverse effects. A drop in temperature of 1° C in one hour lowered the water table 3 cm in the Yolo sand and 12 cm in the Yolo clay with intermediate amounts for soils of intermediate texture.

In the soil columns at steady state, with temperature constant, the soil-moisture system is in delicate balance, water flows through the column at a constant rate, and the pressure potentials throughout the soil mass are steady and dependent upon the permeability of the soil and the velocity of flow. The moisture gradient is fixed by the pressure potential

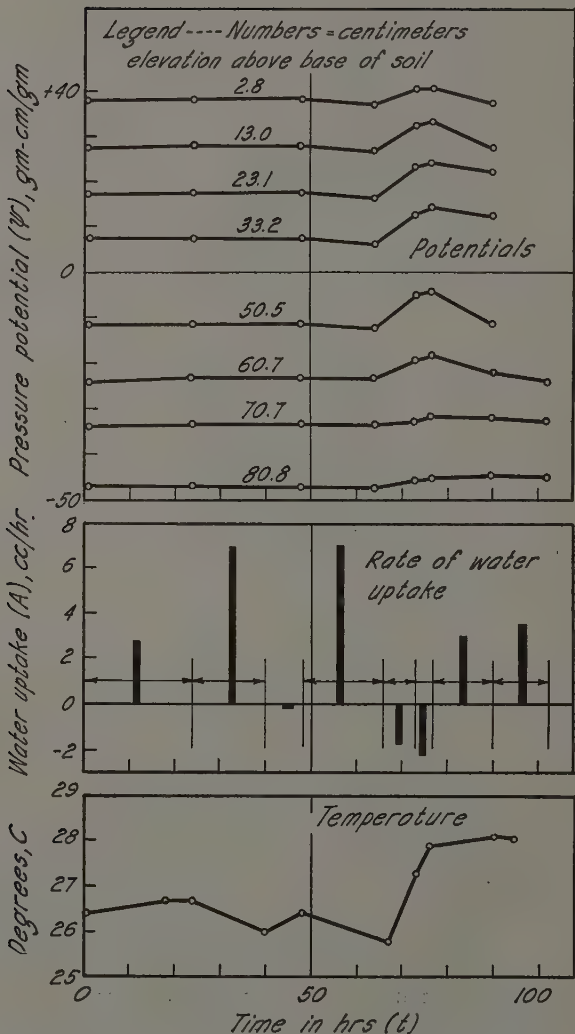


Fig. 8.—The effect of changes in temperature on pressure potentials and rate of water uptake in a column of Yolo fine sandy loam.

gradient, the displacement of which initiates adjustments in the soil-moisture density in the direction of re-establishment of the steady-state gradient.

Surface tension decreases and pressure potential in unsaturated soil increases with increasing temperature. Therefore, an unsaturated soil at a given potential holds less water at a higher than at a lower temperature. After a rise in temperature, water drains downward through the soil, gradually reducing the pressure potentials in the upper portion of the soil column and increasing still further the pressure potentials in the lower portion. During this phase of readjustment, temporary water tables were recorded up to 15 cm higher than the pressure head of the supply line. With decrease in temperature, the cycle described above is reversed; the pressure potentials become more negative, the rate of water uptake increases, and the water table drops.

The magnitude of the potential variations and changes in rate of water uptake with changes in temperature depend upon the rate of temperature change, the permeability of the soil, and the relation of pressure potential to moisture content. If the change in temperature is sufficiently slow or if the soil permeability is sufficiently high, redistribution of water in the soil may take place with sufficient rapidity to maintain relatively constant potentials, and the only obvious major deviation from steady state is the rate of water uptake.

The performance of a column of Yolo fine sandy loam during a period of temperature variation is shown graphically in figure 8. At zero time the pressure potentials in the soil column were at steady state with a rate of water uptake 3.9 cubic centimeters per hour, and a temperature (T) of 26.4° C. The graph may be divided into several time periods for the purpose of discussion:

1. $t = 0$ hours to $t = 24$ hours.
   - A. $\Delta T/\Delta t = +\ 0.013^\circ$ C per hour.
   - B. Small increase in pressure potentials.
   - C. Decrease in rate of water uptake.

2. $t = 24$ hours to $t = 40$ hours.
   - A. $\Delta T/\Delta t = \div\ 0.044^\circ$ C per hour.
   - B. No appreciable change in pressure potentials.
   - C. Great increase in rate of water uptake.

3. $t = 40$ hours to $t = 48$ hours.
   - A. $\Delta T/\Delta t = +\ 0.05^\circ$ C per hour.
   - B. No significant change in pressure potentials.
   - C. Rate of water uptake decreased to a negative value.

4. $t = 48$ hours to $t = 67$ hours.
   A. $\Delta T/\Delta t = -0.032°$ C per hour.
   B. Slight decrease in pressure potentials.
   C. Great increase in rate of water uptake.

5. $t = 67$ hours to $t = 76$ hours.
   A. $\Delta T/\Delta t = +0.23°$ C per hour.
   B. Increase in pressure potentials of 2 gm–cm/gm at 81 cm above the base of the soil column, and increasing progressively to more than 10 gm–cm/gm at the water table. Water flowed downward through the soil and out of the can via the supply line. Greater potentials would have been registered if water had not been lost from the system.
   C. The rate of water uptake became negative. The negative absorption rates shown on the graph do not represent the total amount of water drained out of the soil column. An undetermined amount of water was lost through the vent tube in the constant-level supply reservoir.

6. $t = 76$ hours to $t = 95$ hours.
   A. Temperature changing very slowly and approaching 28.2° C.
   B. Pressure potentials rapidly decreasing toward establishment of of á steady-state gradient approximately equivalent to that at $t = 0$.
   C. Rate of water uptake approaching the rate at the previous steady state.

It is evident that temperature variations may vitiate the accuracy of many types of soil-moisture studies. Fluctuations in soil moisture contents and water tables in field studies may be erroneously attributed to causes other than temperature unless the variations in temperature and their attendant effects are known (*25–27*). The quantitative evaluation of the various effects that temperature variations may have on the soil moisture system would constitute a major problem.

Pressure Potential and Moisture Distribution at Steady State.—Pressure potential and moisture content data in soil columns at steady state are tabulated in table 3, and are represented graphically in figures 9–13. The moisture samples were approximately 10-gram core samples taken with a thin-walled, polished, aluminum tube ½ inch in diameter which was thrust horizontally into the soil column through holes in the side of the soil can. The soil sample was quickly transferred to a weighing bottle by pushing the core out of the sampling tube with a tight-fitting plunger. A soil column was sampled, taking 16 samples, in about 3 minutes.

The tube method of sampling was satisfactory for moisture contents up to approximately 85 to 90 per cent of saturation, but beyond this moisture range very erratic results were secured. Great limitations were imposed on the possible methods for taking samples by the design of the

TABLE 3*

MOISTURE CONTENT AND PRESSURE POTENTIAL; EXPERIMENTAL VALUES FOR YOLO LIGHT CLAY, CAN NO. 2†

Elevation above water table	Wetting		Drying	
	Moisture content, P_w (oven-dry basis)	Pressure potential, ψ	Moisture content, P_w (oven-dry basis)	Pressure potential, ψ
cm	*per cent*	*gm-cm/gm*‡	*per cent*	*gm-cm/gm*
3.5	33.8	− 3.7	.....	− 11.0
8.7	36.0	....	34.92	....
13.9	34.1	− 15.1	.....	− 23.0
19.0	35.8	....	33.53	....
24.2	30.3	− 26.5	.....	− 34.3
29.0	33.8	....	30.58	....
34.1	30.0	− 39.6	.....	− 44.1
39.1	28.7	....	28.60	....
44.2	28.2	− 56.2	.....	− 62.8
49.4	28.0	....	27.55	....
54.6	26.8	− 75.8	.....	− 84.5
59.6	26.4	....	26.49	....
64.6	25.1	− 96.4	.....	−104.7
69.6	24.9	....	24.50	....
74.6	23.8	−134.9	.....	−135.0
79.7	23.4	....	23.15	....
84.8	22.3	−198.8	.....	−200.0
90.0	21.2	....	21.31	....
95.1	19.8	−359.5	.....	−377.6
100.1	....	−599.0	18.54	−610 0
105.1	{14.4	....	.....	....
	{14.7	....	.....	....

* Plotted in figure 11.

† Owing to the limitations of space in this paper, tabular experimental data on the distribution of pressure potentials and moisture is given for one soil column only.

‡ Gm–cm/gm and gm/gm are used throughout this paper as units of work and of force respectively. These values may be multiplied by 980 to obtain dynes and ergs.

soil cans, and the necessity for a minimum disturbance of the soil and alteration of the cross section of the column. The tube method was used for all sampling.

The $P_w = f(H)$ curves (figs. 9–13) were plotted from the experimental data from the lower moisture contents up to 85 to 90 per cent of saturation, and projected from this point to saturation. Experimental values for moisture contents were disregarded in the wet portion of the curve. The zone of saturation was assumed to extend from the base of the soil through the region of positive pressure potentials, and to the

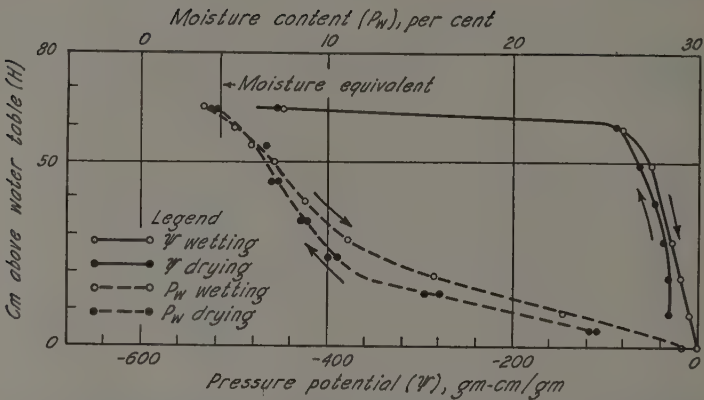


Fig. 9.—Curves of $P_w = f(H)$ and $\psi = F(H)$ for a column of Oakley sand at steady-state wetting and after drainage. For convenience in representation, P_w and ψ are plotted as abscissas.

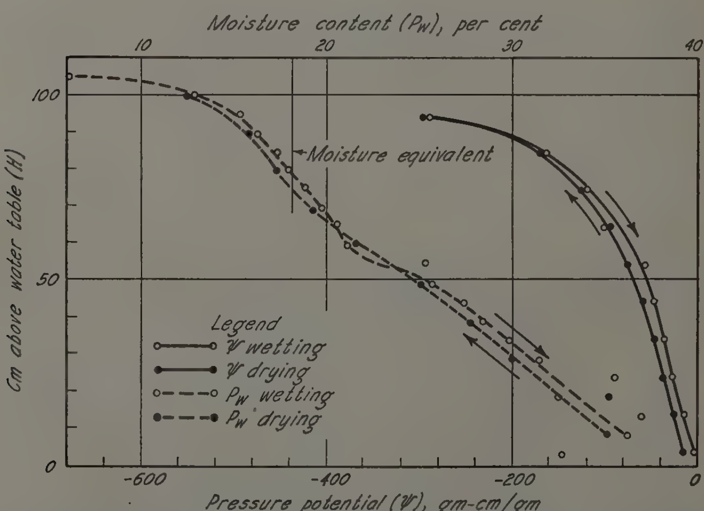


Fig. 10.—Curves of $P_w = f(H)$ and $\psi = F(H)$ for a column of Yolo fine sandy loam at steady-state wetting and after drainage. For convenience in representation, P_w and ψ are plotted as abscissas.

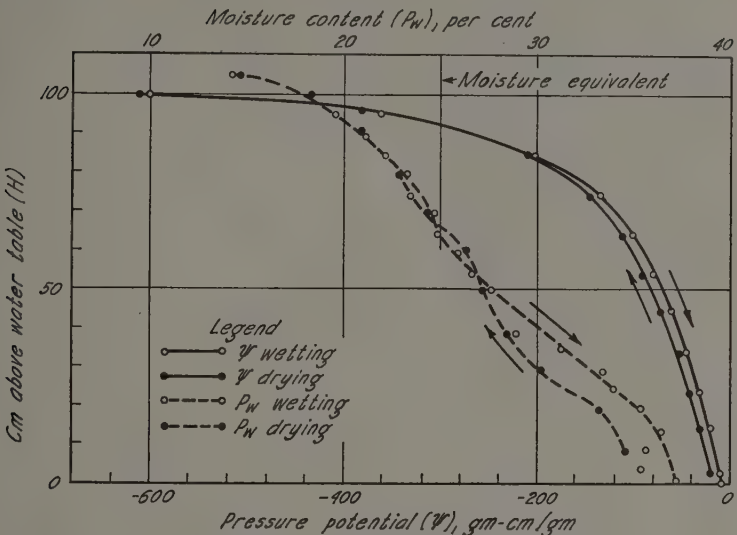


Fig. 11.—Curves of $P_w = f(H)$ and $\psi = F(H)$ for a column of Yolo light clay at steady-state wetting and after drainage. For convenience in representation, P_w and ψ are plotted as abscissas.

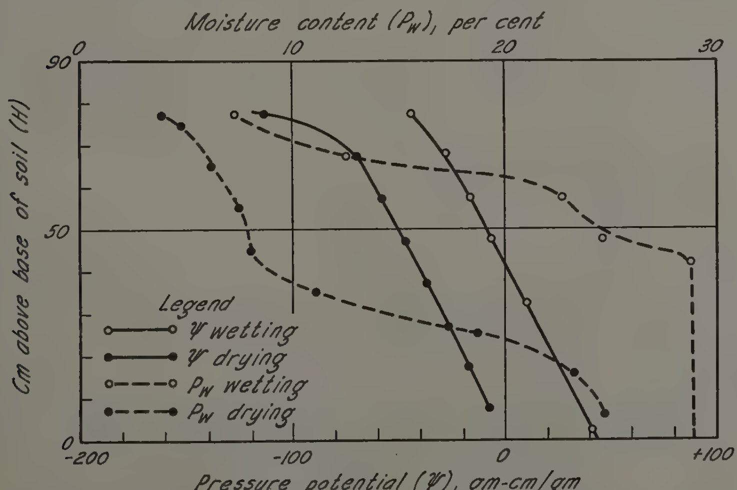


Fig. 12.—Curves of $P_w = f(H)$ and $\psi = F(H)$ for a column of Yolo sand at steady-state wetting and after drainage. For convenience in representation, P_w and ψ are plotted as abscissas.

elevation of zero pressure potential. The moisture content of the soil at saturation was calculated from the apparent density of the soil, assuming a real density of 2.61.

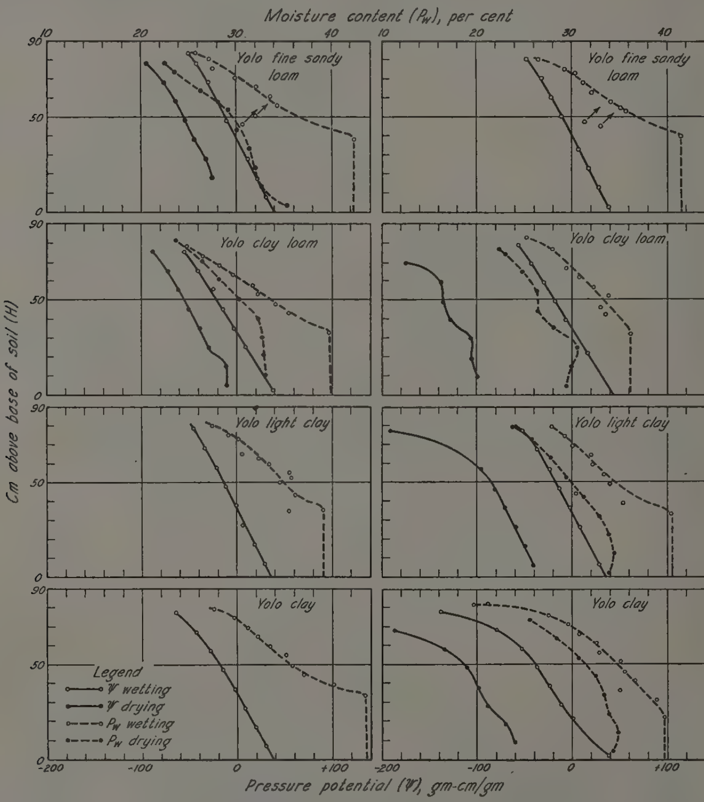


Fig. 13.—Curves of $P_w = f(H)$ and $\psi = F(H)$ for columns of soil at steady-state wetting and after drainage. For convenience in representation, P_w and ψ are plotted as abscissas.

ANALYSIS OF THE PRIMARY EXPERIMENTAL DATA

The Relation between Pressure Potential and Water Content of Soils at 29° C.—The relation between pressure potential, ψ, and moisture content, P_w, in each soil column is represented graphically in curves (figs. 14–18) of $\psi = f(P_w)$. These curves were developed for the soils at a

steady state during the wetting process, and after drainage, from the primary moisture content and pressure potential data as expressed in curves of $P_w = f(H)$ and $\psi = F(H)$.

Differences in vapor pressure and pressure potentials for the same medium at the same moisture content, the magnitude of which depends

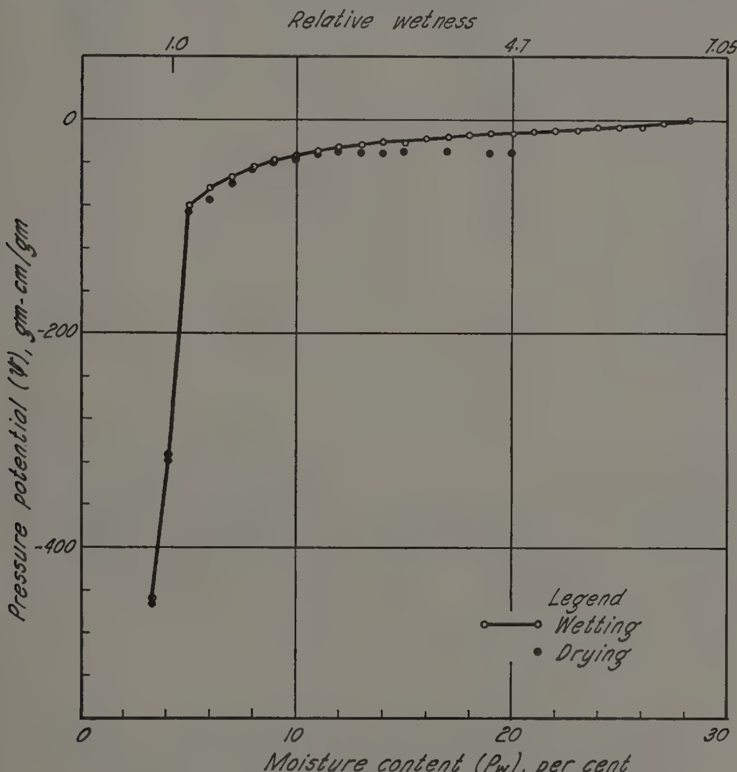


Fig. 14.—Curve of $\psi = f(P_w)$ for Oakley sand wetting and drying.

upon whether the medium is wetting or drying, have often been reported. This phenomenon has been referred to hysteresis effects (*11, 12, 21*), and has been reported in a wide variety of media (*32*) in which capillarity is active in the distribution and retention of liquids. Hysteresis has been attributed by the early workers to the alteration of the contact angle between solid and liquid due to adsorbed air on the solid. Adam (*1*) attributes the alteration of the contact angle to the frictional resistance

between liquid and solid. Smith (*29, 30*) and his associates working with an "ideal soil" attribute maximum, minimum, and intermediate capillary rise to the cyclic alteration in pore cross section incident to any type of packing of spheres. Hysteresis is generally reported for wetting and

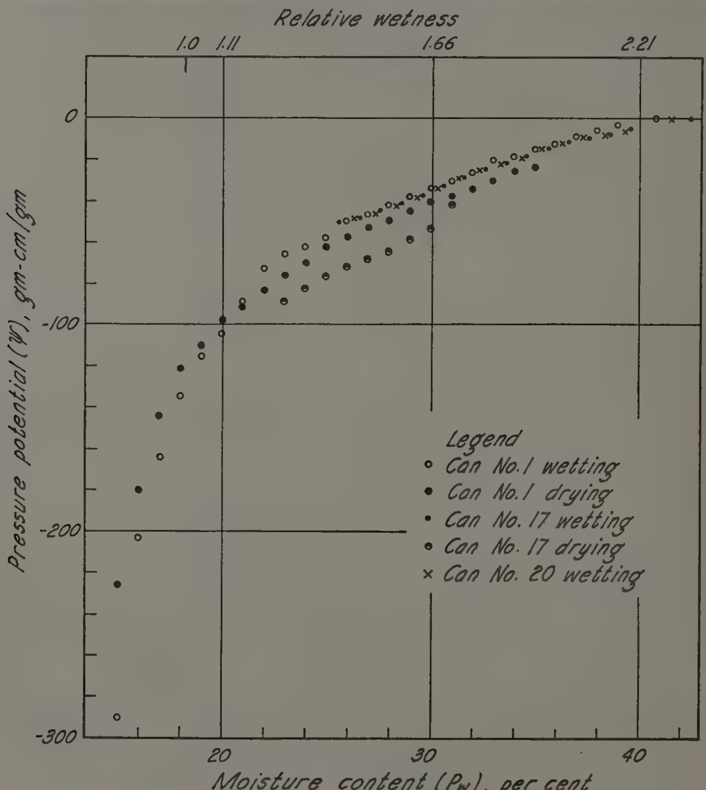


Fig. 15.—Curve of $\psi = f(P_w)$ for Yolo fine sandy loam wetting and drying.

drying clays, and for colloidal separates of clays dried or wetted in evacuated desiccators over osmotic solutions.

In the procedure followed in this experiment, drainage of the soil columns was accompanied by flow of water from the tensiometer cup to the soil, and by settlement and attendant increase in apparent density of the soil. A lag in pressure equilibrium between the tensiometer cup

and the soil would have indicated an apparent hysteresis, but opposite in sign to that observed. At a given moisture content and increased apparent density, the negative radius of curvature would increase and the vapor pressure and the pressure potential should increase. Settlement

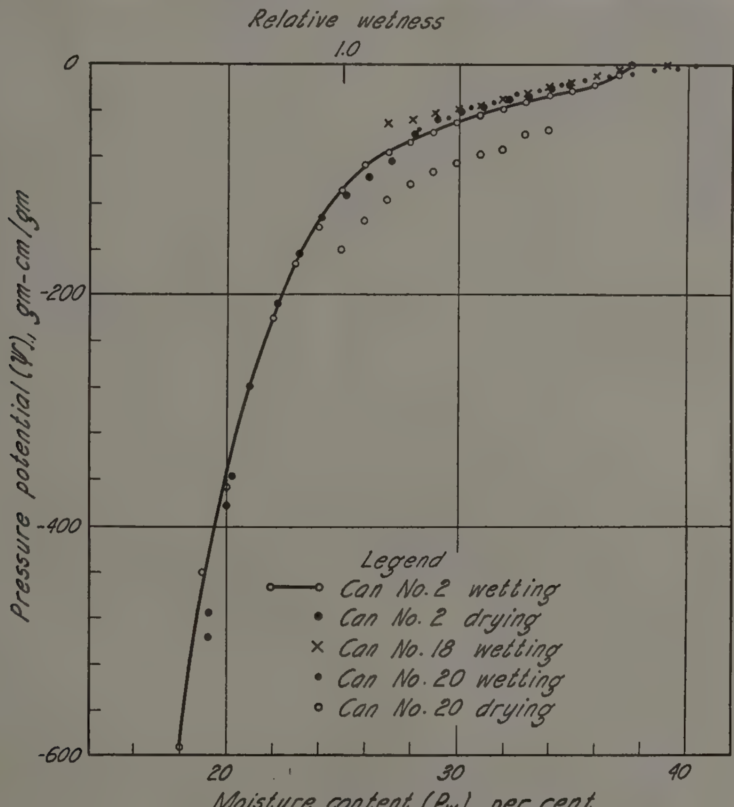


Fig. 16.—Curve of $\psi = f(P_w)$ for Yolo light clay wetting and drying.

of the soil column, then, would result in hysteresis, but opposite in sign to the hysteresis observed.

The differences between the wetting and drying pressure potential curves extend almost to saturation, the range of the negative radii of curvature as calculated from the pressure potentials and surface tension being from 14 to 50 microns. Within this range of moisture content, the solid particles must be entirely bathed with water, and probably no

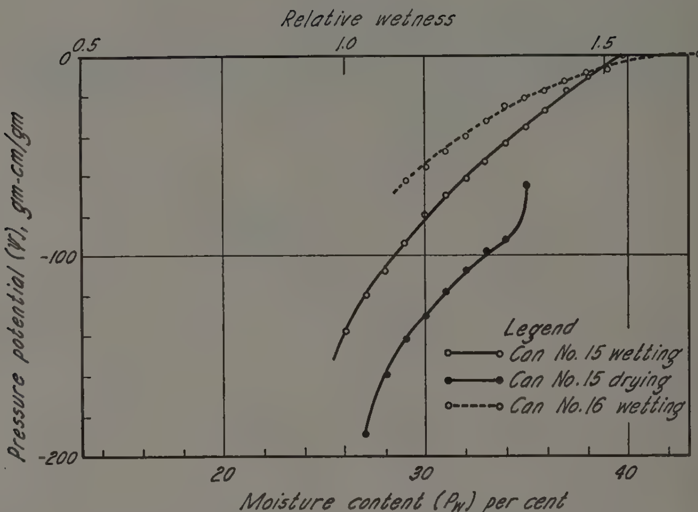


Fig. 17.—Curve of $\psi = f(P_w)$ for Yolo clay loam wetting and drying.

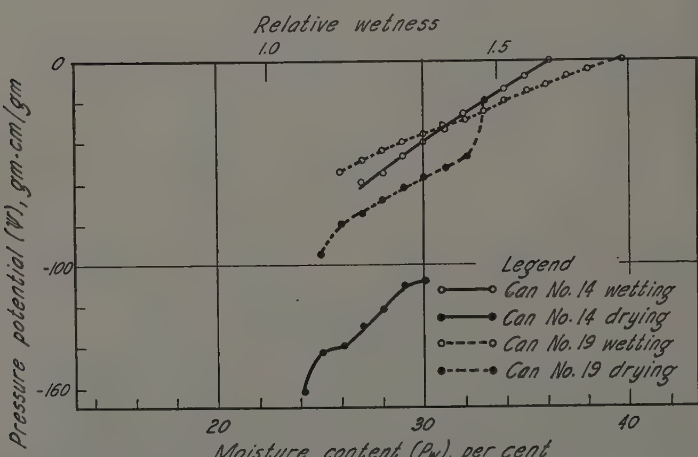


Fig. 18.—Curve of $\psi = f(P_w)$ for Yolo clay wetting and drying.

solid-air interface exists. Under such conditions, adsorbed air on the surface of the solid particles should play little or no part in the curvature of the water-air interface and resulting pressure potentials.

This investigation contributes no positive evidence as to the causative factors in hysteresis; however, the following enumeration of the conditions under which hysteresis was observed may contribute by limiting the field of conjecture as to these factors:

1. At a given negative pressure potential, soils held more water on drying than on wetting.

2. The calculated negative radii of curvature of menisci, within which range the principal hysteresis was observed, were 14 to 50 microns. Hysteresis may persist at radii much less than 14 microns, but under the experimental conditions imposed, drying did not proceed readily below that radius.

3. Soils settled and increased in apparent density as drainage progressed. If an increase in apparent density is the only significant structural change involved in shrinkage, then settlement would result in a higher rather than a lower pressure potential for a given moisture content.

4. As the soils dried, water flowed from the tensiometer cup to the soil. A lag in pressure equilibrium between the cup and the soil would result in a higher, rather than a lower, pressure potential for a given moisture content.

5. The magnitude of hysteresis increased as the range between the wetting moisture content and the drying moisture content increased, as indicated by the following data:

	Can No.	Per cent loss of water during drainage	Approximate hysteresis in gm–cm/gm
Yolo fine sandy loam	1	1	5 to 10
	17	5 to 12	10 to 20
Yolo light clay	2	2	+8 to −8
	20	4 to 6	40
Yolo loam	19	1 to 7	20
	14	5 to 8	70

It has been suggested that tensiometers installed in the soil would be a practicable means of charting the course of the soil moisture status through the relation of pressure potential to moisture content. The above data, however insufficient, indicate that the pressure potential may be not only dual-valued in terms of water content, but that the magnitude of the drying potential may depend upon the range through which the soil dried.

The Permeability of Soils to Water.—In slow motion such as that of water through soils, the velocity of flow, V, may be expressed as a product of the force acting to drive the water through the soil, and of a conductivity function, or the permeability of the soil to water, K. The mathematical expression of flow is given in the equation (*4*),

$$V = KF = -K\nabla(\psi + \omega + \lambda) = -K\nabla\Phi$$

where V represents the mean velocity of flow; F, proportional to V, is the total force per unit of mass acting to drive water through the soil

TABLE 4

VELOCITY OF FLOW OF WATER IN THE SOIL COLUMNS AT STEADY STATE

Soil type and can number		Distance from the water table to the surface of the soil column, centimeters	Depth of water transported to the surface	
			Centimeters$\times 10^6$ per second, V	Centimeters per day
Oakley sand, 3		105	0.23	0.02
Yolo sand, 13		42	0.52	0.04
Yolo fine sandy loam	1	105	0.37	0.03
	17	46	5.30	0.46
	20	42	5.60	0.48
Yolo clay loam	14	51	3.50	0.30
	19	50	5.50	0.47
Yolo light clay	2	105	0.87	0.08
	18	46	6.50	0.56
	20	43	7.10	0.61
Yolo clay	15	60	2.90	0.25
	16	50	5.30	0.46

and is composed of the gradients of pressure potential, ψ; the gravitational potential, ω; and the osmotic potential, λ. The permeability, K, is constant and independent of the rate of flow and the total potential gradient, $\nabla\Phi$.

In applying the general formula to the calculation of permeabilities in the soil columns, V (table 4) is expressed in centimeters per second, $F = - \nabla\Phi$ is expressed in grams per gram, and K has the dimensions of time. The gravitational potential gradient, $\nabla\psi$, is assumed to be constant and equal to one gram per gram. The osmotic potential, λ, is assumed to be constant and the osmotic potential gradient, $\nabla\lambda$, is therefore equal to zero. According to the above assumptions, and under the condition of this experiment in which all movement other than vertically upward or

downward was eliminated, the total potential gradient in grams per gram may be written

$$\nabla\Phi = \nabla\psi + 1,$$

and since the pressure potential gradient at steady state was negative upwards

$$K = \frac{V}{-(\nabla\psi + 1)}.$$

The pressure potential gradient was evaluated at any desired points in the soil column by drawing tangents to the $\psi = f(H)$ curve for that column and determining their slope.

In this discussion of the permeability of soil to water, it is not intended to introduce new terms. In the interest of clarity, however, it is necessary to restate the definition of terms that will be frequently used:

Saturated permeability refers to the permeability of the soil when the soil is saturated with water. Saturated soil is a two-phase system, solid and liquid.

Unsaturated permeability is the permeability of the soil when it is unsaturated. Unsaturated soil is a three-phase system, solid, liquid, and gas. Unsaturated permeability is based on the flow of water through the soil in the vapor phase, or in the vapor and liquid phases.

Capillary permeability refers to liquid flow in unsaturated soil.

Vapor permeability refers to vapor flow in unsaturated soil.

The configuration of the moisture system, in soil at various degrees of unsaturation, has been amply discussed elsewhere in the literature; here, it is sufficient to say that vapor flow will take place in unsaturated soil at any total potential gradient other than zero. Capillary flow can take place only at those soil-moisture contents at which the water films are so connected as to allow liquid water to flow through water films from one position in the soil to another. *Continuous water films* are those which permit water, in the liquid phase, to flow through water films from one position in the soil to another. Water films are termed discontinuous when water in the liquid phase cannot flow through water films from one position in the soil to another. Continuous water films must be connected, but discontinuous water films may also be connected, the sole criterion for continuity, as here used, is that of flow as described above. If the soil moisture films are continuous, capillary flow will take place at any total potential gradient other than zero. If the soil moisture films are discontinuous, capillary flow is zero (*18*).

Permeability as a Function of Pressure Potential.—Soil permeability is measured per unit of cross-sectional area of soil. Since capillary flow

takes place through moisture films, we would expect capillary permeability to increase with increasing effective cross section of moisture films, and hence with increasing moisture in the soil. In this study the moisture content has been expressed as a function of pressure potential, ψ, which is directly related to the vapor pressure of the soil moisture, and is an

TABLE 5*

WETTING AND DRYING POTENTIALS AND PERMEABILITY AS FUNCTIONS OF MOISTURE CONTENT; YOLO LIGHT CLAY, CAN NO. 2

P_w	Wetting		Drying	
	ψ	$K\dagger \times 10^6$	P_w	ψ
18	−592	0.012	....	.....
19	−440	0.022	19.2	−476
20	−366	0.041	20.2	−358
21	−278	0.064	21.2	−280
22	−224	0.091	22.2	−208
23	−172	0.133	23.2	−162
24	−140	0.215	24.2	−126
25	−108	0.398	25.2	−111
26	− 86	0.795	26.2	− 98
27	− 76	0.88	27.2	− 82
28	− 67	0.97	28.2	− 60
29	− 58	1.06	29.2	− 48
30	− 50	1.21	30.2	− 41
31	− 44	1.48	31.2	− 36
32	− 37	1.91	32.2	− 31
33	− 32	2.56	33.2	− 28
34	− 27	3.30	34.2	− 23
35	− 22	4.40	34.9	− 16
36	− 16	6.15	....	.....
37	− 8	8.60	....	.....
37.5	0	12.3	....	.....

* Owing to the limitations of space in this paper, tabular experimental data on the distribution of pressure potentials and moisture is given for one soil column only.

† Permeability, K, was calculated from the velocity of flow, V, expressed in centimeters per second and the pressure potential gradient, $\nabla\psi$, expressed in grams per gram. The values for V were taken from table 4, and the values for $\nabla\psi$ were taken as the slope of the curve of $\psi = F(H)$ in figure 11.

especially useful function of the soil moisture density because it is also an index of its configuration. Accordingly, unsaturated permeability will be investigated as a function of ψ (table 5 and figs. 19, 20).

Permeability is maximum at, or near, a pressure potential of zero for all the soils covered by this experiment. The permeability remains constant from zero pressure potential down to pressure potentials of — 10 to — 40. Saturation persists for some distance above the plane of zero-pressure potential, but this distance could not be determined by the method used for taking moisture samples. This height was probably from 1 to 3 centimeters above the plane of zero-pressure potential, and

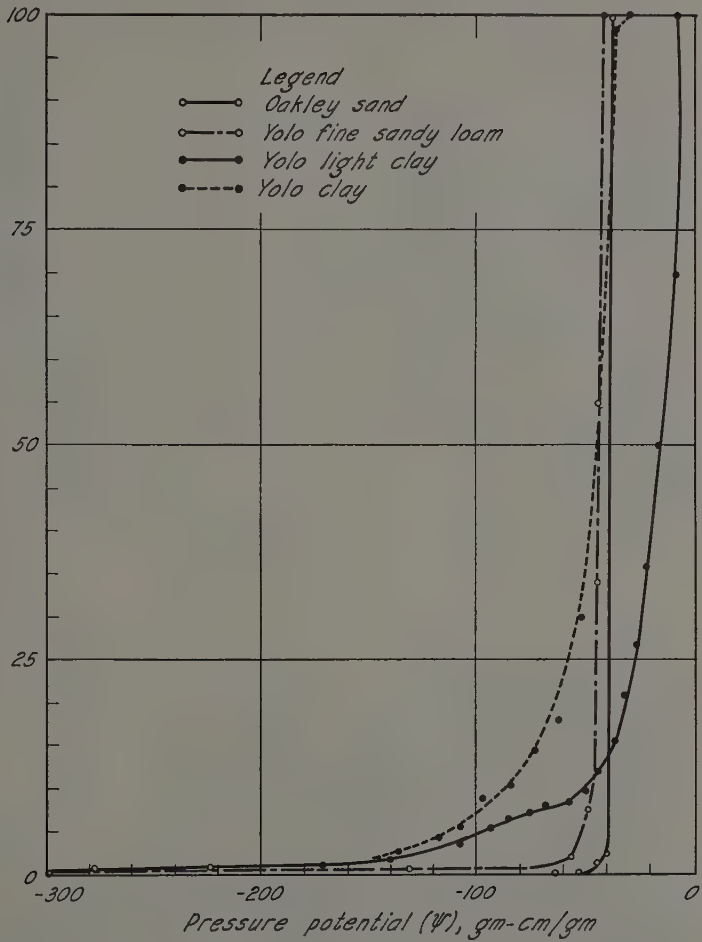


Fig. 19.—Permeability as a function of pressure potential, $K = f(\psi)$ with permeability expressed as a percentage of the permeability at a pressure potential of zero.

was entirely too small to account for the high permeability extending 20 to 30 centimeters above the piezometric surface.

Permeability of the Yolo clay was less in the range of positive pressure than that at pressure potentials of zero to —40 gm–cm/gm. Under certain conditions differential swelling of soil colloids effected by wetting at

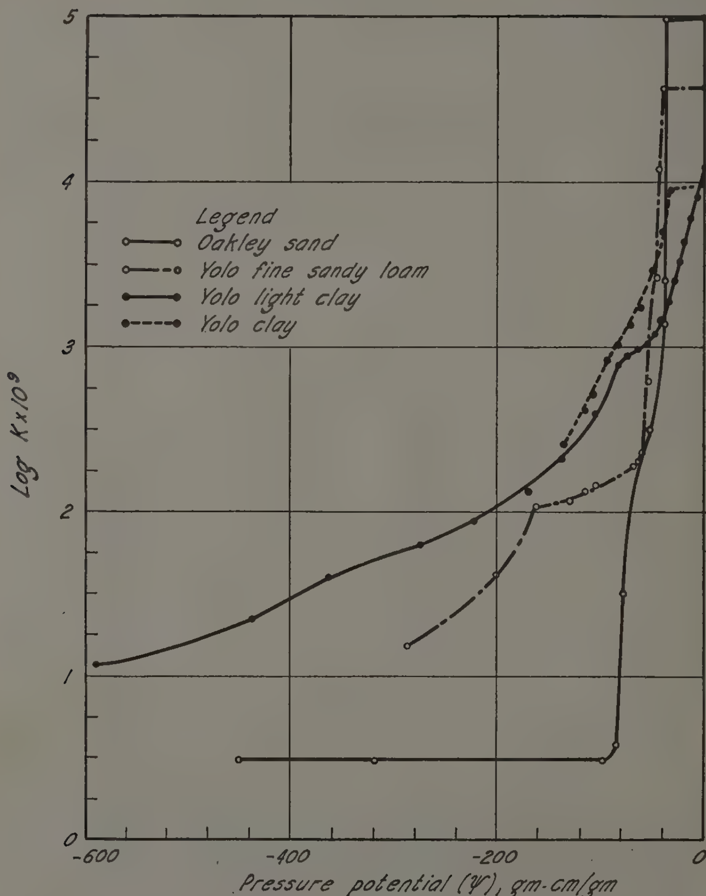


Fig. 20.—The logarithm of the permeability times 10^9 as a function of the pressure potential, $\log (K \times 10^9) = f(\psi)$, plotted for four soils. $K = -\frac{V}{\nabla \Phi}$, in which V is expressed in cubic centimeters per second, and $\nabla\Phi$ in grams per gram.

different pressure potentials may result in a greater permeability above the piezometric surface than that in the range of positive pressure. Yolo clay swells on wetting, but no change in the over-all volume of the soil was detected in the cans. In such swelling the solid particle with its absorbed water may act as a larger solid particle, as far as the permeability

of the swollen soil is concerned. This would result in a greater effective volume of solid and lesser effective volume of pore space per unit volume of soil, and likewise, a lower total effective pore area and fewer continuous pores per unit of cross-sectional area of the soil column. If the soil colloids swell in proportion to the pressure potential at which they are wetted, the total pore space effective in the conduction of water in the soil columns would decrease as this potential increased. Hence the per cent of effective pore space in the range of positive potentials would be less than in the range of negative potentials, and permeability may be greater for some distance above the piezometric surface than that obtained below this surface.

The Effect of Texture on Soil Permeability.—The effect of texture on the manner with which permeability changes with pressure potential is shown in figures 19 and 20. For the soils studied, saturated permeability increases with increasing coarseness of texture. In the range of capillary flow, the rate of change of permeability with pressure potential, $\partial K/\partial \psi$, increases with increasing coarseness of texture, such as to produce the reversal of permeabilities shown in figure 20. The soils arranged in permeability series are, at saturation:

sand > fine sandy loam > light clay > clay

and at $\psi = -100$

sand < fine sandy loam < light clay < clay.

Zero Capillary Permeability.—The evaluation of the soil moisture content, or the pressure potential in the soil at which capillary conductivity becomes zero, is of importance in the study of soil-moisture problems, such as: the distribution of water in the soil, the translocation of soluble salts, the maximum height of capillary rise, etc. Richards (*18*) states that the water in soils is no longer present in a continuous liquid phase, and capillary flow ceases at the point where capillary conductivity becomes zero. At field capacity or at the normal moisture capacity the capillary permeability of soils must be zero or approximately zero and any water translocation must take place in the vapor phase (*13, 22, 33, 34*).

In this paper zero capillary permeability is discussed under the two criteria: the pressure potential of the wetting front, and the pressure potential at which $\partial K/\partial \psi = 0$.

The advance of the wetting front was observed in the soil columns through celluloid-covered holes in the soil cans. Core moisture samples were taken at the wetting front with a ¼-inch cork borer, care being taken to include no dry soil. The center of the core was about $\frac{3}{16}$-inch

below the wetting front. Since there was a moisture gradient in the soil column with the moisture density increasing with distance below the front, the samples may show a higher moisture content than that of the wetting front. The increase in the experimental value for moisture content due to a moisture gradient could not be determined because the gradient itself could not be evaluated. The moisture gradient, however, decreases with increasing height of rise; and if the effect of the moisture

TABLE 6

Moisture Content at Wetting Front for Three Yolo Soils

Fine sandy loam, can No. 17		Light clay, can No. 20		Clay, can No. 16	
Elevation of sample	P_w	Elevation of sample	P_w	Elevation of sample	P_w
cm	*per cent*	*cm*	*per cent*	*cm*	*per cent*
13.1	19.9	7.6	24.6	19.9	26.1
20.4	19.6	10.3	25.1	30.0	26.8
23.2	20.2	27.6	24.3	40.1	24.9
27.9	21.0	35.2	24.0	50.3	25.9
33.4	20.5	37.8	24.4	70.5	25.6
35.9	20.8	40.5	24.1	....	....
40.6	21.6	50.5	25.9	....	....
50.7	19.8	....	....	....	....
70.9	20.6	....	....	....	....
81.1	19.7	....	....	....	....
Mean P_w (per cent)	20.4	....	24.6	....	25.9
ψ (gm–cm/gm)*	−92	....	−120	....	−140

* ψ values taken from $\psi = f(P_w)$ curves.

gradient is appreciable, the moisture content of the wetting front samples should decrease from the bottom of the soil column to the top. No such relation was found; the wetting front samples showed a relatively uniform moisture content throughout the length of the soil columns. Table 6 lists wetting front moisture contents with the elevation of the front above the base of the soil columns.

Wetting front samples were not taken from the Oakley sand; but from the nature of its curve of $\psi = f(P_w)$ it is assumed to be at a pressure potential of approximately — 80 gm–cm/gm, and a moisture content of 5.0 per cent.

The following experimental observations, along with certain theoretical considerations, may aid in characterizing the wetting front:

1. Water advances in a front from wet to drier soil under the influence of capillarity (*14, 36*). Beyond the front, the soil remains apparently dry, and immediately at and behind the front, the soil is apparently

completely wetted. Macroscopically, there is a sharp line of demarcation between the obviously wet soil and the obviously dry soil.

2. The moisture content of the wetting front determined by sampling is constant, indicating a constant potential and a constant radius of curvature. The pressure potential of the wetting front ranged from — 80 gm–cm/gm for the Oakley sand to — 140 gm–cm/gm for the Yolo clay with intermediate values for soils of intermediate texture.

3. The moisture content of the dry soil immediately beyond the wetting front was not definitely known. The air-dry soil was in equilibrium with air at a relative humidity of approximately 42 when wetting began. As the first approximation we may assume a relative humidity of 50 at a distance of 1 mm beyond the wetting front making the pressure potential gradient across this region 1×10^7 gm/gm. These assumptions may be in appreciable error, but whatever logical values are assumed, the pressure potential gradient from the dry soil to the wet is obviously very great.

4. The existence of a great pressure potential gradient from the dry soil to the wetting front should insure the maintenance of the lowest possible pressure potential, and hence, the thinnest possible moisture films at the front consistent with continuous moisture films behind the front.

5. We may adapt the explanation given by Adam (*1*) for the rise of water in capillary tubes to the rise of water by capillarity through a porous medium such as soil, although it is recognized that the capillary tube is filled with water back of the advancing meniscus, and in unsaturated soil the water films are only partly bounded by a solid.

A. The liquid is not pulled through the soil by a hypothetical tension acting on the film which clings to and climbs up the surface of the soil particles.

B. The energy relations determine what the stable contact angle shall be.

C. The fluidity of the liquid permits the molecules to move about until they generate that angle.

D. The contact angle and the dimensions and shape of the voids between the solid particles, determined by the effective texture and packing arrangement, govern the curvature of the liquid-air interface.

E. The pressure difference arises from the free energy resident in the liquid-air interface.

F. The liquid then flows up under the hydrostatic pressure.

Disregarding for the present the translocation of water through soil in the vapor phase and the possibility of the establishment of continuous

moisture films through the agency of vapor flow, we may characterize the wetting front and some of its relations to the soil-moisture system in general from the five preceding observations:

1. The wetting front represents an irregular surface of discontinuity with continuous moisture films behind the front, and discontinuous or nonexistent films beyond the front.

2. At moisture contents below that characteristic for the wetting front, the capillary permeability of a soil to water in the liquid phase is zero. At these lower moisture contents the films are discontinuous, and there is no mechanism for liquid flow.

3. The magnitude of the pressure potential gradient from the dry soil to the wetting front has no influence on the rate of advance of this front except that a wetter soil requires less water to establish continuous films than a drier soil. The advance of the wetting front is by liquid flow, and is proportional to the pressure potential gradient back of the wetting front. The water flows under hydrostatic pressure.

4. At a given temperature, the curvature of the moisture films at the wetting front is characteristic for the soil solution and the soil, and does not vary with elevation of rise.

5. The moisture content at the wetting front is constant for a given soil solution and soil.

6. At constant temperature, the pressure potential at the wetting front is constant for a given soil solution and soil.

7. Water cannot rise by capillarity beyond the elevation at which the sum of the gravitational potential, the osmotic potential, and the pressure *potential characteristic of the wetting front* is equal to zero.

All the considerations thus far with reference to the wetting front have concerned only liquid flow through soils without the necessary intervention of vapor flow which is always present in a three-phase system. The soil has also been considered as a granular solid of constant effective texture and structure. The changes in the effective texture and structure with wetting cannot be completely described. It is known, however, that the mass effect of these changes is relatively insignificant in coarse-textured soil, but may be of considerable magnitude in other soils. Swelling of the colloidal fraction due to wetting is the only change in the solid phase that will be considered.

With the wetting front advancing rather rapidly through air-dry soil, the structure and effective texture immediately beyond the wetting front is probably very much the same as that which is characteristic for the

dry soil. When the wetting front approaches its maximum height above the water table and advances more slowly, wetting of the soil in advance of the front through the agency of vapor flow is of greater relative magnitude, the soil colloids swell, a lesser radius of curvature of the liquid surface may establish continuous moisture films, and the pressure potential of the wetting front may decrease progressively as the front advances from the water table to the maximum height of capillary rise. Experimental evidence is not at hand to permit a quantitative evaluation of the factors in the above speculation. For the present it seems worth while to bear these factors in mind, although they have not been determined, and though eventually they may be found to be of little significance.

Unsaturated permeability cannot be separated experimentally into its components of vapor and liquid permeability. If, however, we assume that vapor permeability for a given soil is constant when liquid permeability is zero, then liquid permeability would be zero when $\partial K / \partial \psi = 0$. In figure 19 the permeability of four soils is plotted as a function of the pressure potential. The permeability at each potential is expressed as a percentage of the permeability at zero pressure potential. The values for the pressure potentials at which capillary permeability becomes zero, as determined from moisture samples taken at the wetting front, are: Yolo fine sandy loam, — 92 gm–cm/gm; Yolo light clay, — 120 gm–cm/gm; and Yolo clay, — 140 gm–cm/gm. These potentials referred to the curves of $K = f(\psi)$, however, are not at values of ψ at which $\partial K / \partial \psi = 0$. But below these potentials both K and $\partial K / \partial \psi$ are very small. It is indicated that the potential at the wetting front represents, at least to the first approximation, the potential below which discontinuity occurs in the soil-moisture system, and is a critical point on the permeability curve at which capillary permeability becomes approximately zero. It is also indicated that the determination of the wetting front potential by sampling for moisture content is a practicable experimental procedure. This is worthy of further investigation.

INTERPRETATION OF SOME SOIL MOISTURE PHENOMENA IN TERMS OF PERMEABILITY

The Moisture Equivalent.—The moisture equivalent has been considered as representing a point on the pressure potential curve at which the pressure potential gradient of the soil is in approximate equilibrium with the centrifugal force applied, or at which the pressure potential is equal to —1000 gm–cm/gm (*21*). According to the data presented in this paper, the pressure potential at the moisture equivalent is much greater than — 1000 gm–cm/gm, varies with the texture of the soil, and repre-

sents the approximate ψ on the $K = f(\psi)$ curves at which the water in the soil becomes discontinuous, and the capillary permeability becomes zero.

Vapor permeability is high in sands. In centrifuging, the combined vapor and liquid flow reduces the moisture content of sand in the centrifuge cup to a pressure potential below that at which capillary flow ceases. In heavy clay the vapor permeability is low. The combined vapor and liquid flow is not sufficient to reduce the pressure potential of heavy clay to the point at which capillary flow ceases. The fact that the moisture equivalent of clay is generally higher, and of sands is generally lower than the field capacity would be expected from the above considerations of permeability.

Hysteresis of Curves of $pF = f(P_w)$.—An adaptation of a technique originally proposed by Bouyoucos (*5*) has been used for the derivation of data for the development of $\text{pF} = f(P_w)$ curves. The equipment required in this technique is: a source of vacuum, a Büchner flask, and filter paper coated with a thin layer of silt. The silt-coated paper forms a porous plate of small pore dimension. To determine the drying pF, a thin layer of soil is placed on the filter paper, and a continuous liquid phase is established extending through the filter plate, funnel, and stem, and into the filter flask. A constant vacuum is applied to the flask for a time considered sufficient to remove excess water. At the end of the drying time the soil is removed from the filter and the moisture content determined. The pF at that moisture content is assumed to be equal to the logarithm of the negative pressure applied. A drying curve of $\text{pF} = f(P_w)$ is developed from values of pF and P_w derived by repeating the procedure at different suction pressures. The technique for deriving the wetting pF is the reverse of that used in drying. In wetting, air-dry soil takes up water against a constant negative pressure maintained in the continuous liquid phase.

The assumptions necessary for the application of pF data derived by the above technique are:

1. At the end of the wetting or drying time, the pressure in the soil moisture films is at approximate equilibrium with the negative pressure applied.

2. The moisture films are continuous from the water in the flask through the soil layer.

The first assumption can only be valid within that moisture range in which the second assumption is true, since this technique is an approximate and rapid method for determining pF, and is applicable only if

water transfer can take place in the liquid phase. The time allowed for each determination is obviously too short to allow establishment of equilibrium moisture conditions through the agency of vapor flow.

The above-described technique, used at pressure potentials below which capillary permeability equals zero, would give erroneous results. On drying, the soil would lose water readily down to the pF at which the capillary permeability becomes zero. Further loss of water would be very slow through the agency of vapor flow. The experimental drying moisture content and pF would be higher than the true values representing equilibrium with the suction applied. On wetting, no capillary flow could take place, and the soil would receive water only by condensation of water vapor. The experimental wetting moisture content and pF would be lower than the true values representing equilibrium with the suction applied.

Curves of pF $= f(P_w)$ derived by the above technique show hysteresis of considerable magnitude between the wetting and drying curves. At a given pF the moisture content in the drying curve is much higher than that in the wetting curve. It is suggested that many of the data were secured in the moisture range in which the moisture films were discontinuous and the capillary permeability was zero; and that approximate pressure equilibrium was not established between the soil water and the water in the filter pores.

Moisture Distribution in Stratified Soils.—It is a well-known fact that a heavier-textured soil, underlaid by a coarse-textured soil, has a higher field capacity than the unstratified heavier soil (*2*). This phenomenon can be explained on the basis of the characteristic pressure potential for each soil at which capillary permeability becomes zero. To illustrate this point, let us consider two columns of soil as follows:

1. Column of unstratified Yolo clay
   A. K is approximately zero at $\psi = -140$
   B. $P_w = 26$ per cent at $\psi = -140$.
2. Column of Yolo clay stratified with Oakley sand; K of Oakley sand is approximately zero at $\psi = -80$.

After irrigation of the unstratified Yolo clay, water will flow downward under the influence of gravity until the moisture films become discontinuous. The final moisture distribution in the soil, neglecting vapor flow and in the absence of a water table, would be at $\psi = -140$ and $P_w = 26$ per cent.

After irrigation of the stratified column, water will flow downward through the clay with a pressure potential at the wetting front of ap-

proximately — 140. When the wetting front reaches the sand, flow cannot take place until the potential in the clay becomes greater than — 80 which is the minimum pressure potential at which flow is possible in the sand. (For Yolo clay $P_w = 30$ at $\psi = -80$.) The equilibrium moisture distribution in the clay, neglecting vapor flow, will be:

Distance above sand in centimeters	ψ	P_w
0	—80	30
0 to 60	—80 to —140	30 to 26
Above 60	—140	26

If we assume the same two soil columns, ideally, under conditions of capillary rise:

1. With the top of the sand stratum less than 80 centimeters above the water table, the height of capillary rise will not be affected. At equilibrium, capillary water will rise to 140 centimeters above the water table.
2. If the bottom of the sand stratum is at any elevation between 80 to 140 centimeters above the water table, capillary rise will stop at 80 centimeters or at the bottom of the sand stratum.
3. If the sand stratum occurs so that a point 80 centimeters above the water is in sand, then capillary rise will reach its maximum in the sand at 80 centimeters above the water table. Theoretically, a shift of a few millimeters in the elevation of the sand stratum may make a difference of 60 centimeters in the maximum height of capillary rise.

SUMMARY

Data on the permeability of soils to water under saturated conditions is abundant; however, the unsaturated permeability of soils has received relatively little study, and published data on the subject are meager. The introduction of the potential function gave rise to the dynamic method in the study of unsaturated flow, and the development of the tensiometer instrument has made possible the direct determination of pressure potentials.

All published data now available on the permeability of soil to water in unsaturated flow were derived by the dynamic method from pressure potentials determined directly from tensiometers placed in the soil. This method was used in the soil-permeability studies reported in this paper.

Six soils, ranging in texture from sand to clay, were investigated under laboratory conditions of capillary rise. The soils were placed in metal cylinders with water supplied to their bases at a constant pressure sufficient to establish saturated conditions in the lower portion of the columns. Water flowed upward through the columns under the influence

of positive hydrostatic pressures in the saturated zone, and of negative hydrostatic pressures, or by capillarity, from the water table to the surface of the columns where it was removed by evaporation.

Pressure potentials in the unsaturated soil were studied as functions of moisture contents by determining the pressure potentials, ψ in gram-centimeters per gram, directly from tensiometer readings and the moisture contents, P_w, by sampling the soil columns. The relation between ψ and P_w for each soil was represented graphically in curves of $\psi = f(P_w)$. Hysteresis in the relation of ψ to P_w was found for all the soils, according to whether they were wetting or drying. At a given P_w, ψ was less after drainage than during the wetting process. The data of this experiment also indicate that for soils drying, the pressure potential depends upon the range through which the soil has dried.

The pressure potential in an unsaturated soil at constant moisture content increases with increasing temperature, and the amount of water held in the soil at a given pressure potential decreases with increasing temperature. During periods of temperature change in a soil column in which there is a high water table, these relations cause wide variations in the rate of water uptake from a water table. Under field conditions, rapid changes in soil temperature above a water table would be accompanied by rising water tables with rising temperature, and falling water tables with falling temperature.

The pressure potential of the water films in a soil is a measure of the curvature of the films and an index of the degree to which the soil is saturated. The relation of soil permeability, K, to pressure potential was studied and curves of $K = f(\psi)$ were developed. K could also be studied as a function of P_w through the relationship between ψ and P_w. Permeability was a maximum at or near saturation and decreased rapidly with decreasing P_w to approximately the moisture equivalent of the soil, at which moisture content the permeability was very low and remained constant or decreased only slightly with further decreases in moisture content. At this point $\partial K / \partial \psi = 0$ (approximately). This moisture content is also approximately that of the wetted front generated as the water advanced upward through the dry soil above a water table. These two criteria, the P_w at which $\partial K / \partial \psi = 0$ and the P_w of the wetting front, are interpreted as representing the P_w at which the moisture films in the soil become discontinuous and at which the capillary permeability of the soil is zero.

The texture of a soil affects permeability by its influence on the size, number, and continuity of the interspaces or pores. For soils of a like nature, such as the members of a single soil series, the size of pores de-

creases and the number of pores increases with increasing fineness of texture. The soils used in this experiment, arranged in order of permeability are, for saturated flow

sand > fine sandy loam > light clay > clay

and for unsaturated flow at $\psi = -100$

sand < fine sandy loam < light clay < clay.

If arranged in order of decreasing pressure potential at which unsaturated flow is approximately zero, the sequence obtained is:

sand > fine sandy loam > light clay > clay.

Knowledge of the variation of permeability with texture, especially the pressure potential at which capillary permeability is approximately zero, is fundamental to the consideration of the relative rates and maximum height of capillary rise, to the field capacity in stratified and nonstratified soils, and to single-valued "constants" such as the moisture equivalent, the field capacity, and the normal moisture-holding capacity. These experiments indicate that the pressure potential of the soil moisture at these constants varies with the texture of the soil. They are at the approximate ψ on the curves of $K = f(\psi)$ at which the moisture films in the soil become discontinuous and the capillary permeability becomes zero.

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SOIL MACROSTRUCTURE AS AFFECTED BY CULTURAL TREATMENTS

RALPH C. COLE

SOIL MACROSTRUCTURE AS AFFECTED BY CULTURAL TREATMENTS[1]

RALPH C. COLE[2]

INTRODUCTION

THIS INVESTIGATION was undertaken to find a quantitative method of expressing the structural condition of the soil, and by means of this method to study the effects of various mechanical treatments with respect to changes in structure. The effects of irrigation and of tillage operations were of particular concern. Seasonal changes were also observed.

Shaw (*17*)[3] has defined soil structure as:

> A term expressing the arrangement of individual grains and aggregates that make up the soil mass. The structure may refer to the natural arrangement of the soil when in place and undisturbed or to the soil at any degree of disturbance. The terms used indicate the character of the arrangement, the size and shape of the aggregates, and in some cases may indicate the consistence of those aggregates.

As thus defined, the term "soil structure" is obviously descriptive, and as such is not capable of being expressed by any specific measurement or number.

Many measurements of the physical properties of soils, which are dependent on the structure, have been made; and any of these measurements may be considered as an index of soil structure. These measurements are made either of the macro- or microstructure. A greater amount of work has been done on the microanalysis, which has been mainly measurements of the size distribution of particles after the soil has been slaked in water. The macroanalyses have been mainly measurements of the size distribution of coarse aggregates of soils obtained under field conditions in an undisturbed state. This present investigation is of the latter type; the method will be described in detail later. Other methods, such as the pull on the drawbar of a tillage implement, the amount of pressure required to force a sharpened instrument into the soil, and porosity measurements such as water penetration, air movement, so-called "capillary and noncapillary" pore space, and measurements of volume weight, have been used as indexes of soil structure.

[1] Received for publication November 1, 1937.

[2] Instructor in Soil Technology and Junior Soil Technologist in the Experiment Station.

[3] Italic figures in parentheses refer to "Literature Cited," at the end of this paper.

The work here reported was carried out on soils of the Yolo, Denverton, and Capay series, on the University Farm at Davis, California, and on private farms nearby. Quantitative measurements were made of the changes in the size distribution of aggregates after tillage operations and irrigations, and of changes directly attributable to changes in the seasons. The studies on the effect of tillage operations were made in orchards, in fields in the preparation of seedbeds, and in test plots for special-study purposes.

The tillage operations in orchards were for the express purpose of controlling weeds. Those in the preparation of seedbeds were variable and dependent upon the season in which the crop was to be planted and the nature of the crop itself. In some of the seedbed preparations, preirrigations were made to insure an adequate moisture supply before seeding.

REVIEW OF LITERATURE

In this brief review of literature, no attempt is made to discuss all of the work that has been done on soil structure. A few papers dealing with each phase are mentioned, even though some of them bear rather indirectly on this investigation.

Russell (*15*), at Rothamsted, investigating the factors of importance in crumb formation in soils, found that clay particles can form strong aggregates or crumbs when dry, only if the clay particles are sufficiently small, if there are a sufficient number of small exchangeable ions on the clay, and if the clay has been dried from a dispersion medium whose molecules are polar and sufficiently small. Tiulin (*18*) in Russia, Demolon and Henin (*9*) in France, Novak (*14*) in Czechoslovakia, Bouyoucos (*2*), Baver and Rhodes (*1*), and Cole and Edlefsen (*6, 10*) in the United States, all have measured water-stable aggregates by sedimentation, or by wet sieving and sedimentation, as indexes of soil structure. In most cases, these workers recognize that certain aggregates are fairly stable in water, and that in some cases very drastic treatments are necessary to break them down materially. Demolon and Henin (*9*) and Tiulin (*18*) describe soil aggregates as being of two kinds: those that are water-stable are formed with clays whose base-exchange cations are dibasic, and those stable only in the dry condition are formed from compression, or with clays whose base-exchange cations are monobasic. All of the workers referred to are in accord in the belief that the formation of aggregates takes place as soils are being dried out. Vilensky (*20*) has shown that soils which give the greatest stability against slaking and require the greatest force for deformation of dry aggregates have definite moisture ranges.

In macroaggregate analysis, the work of Keen (*12*) and his associates is among the first. In this work, samples were obtained during tillage operations by cutting out rough cubes of soil with a spade and transferring them to a nest of sieves. The sieves were gently shaken a definite number of times and the material retained on each sieve was weighed. Chapman (*5*) observed that two plots on the North Dakota Experimental Farm were widely different in structure and measured this difference by sieve analysis of air-dry samples taken from each plot. Hoffman[4] determined the size distribution of aggregates before and after tillage with various kinds of implements. He used a 14-inch cylinder, which was driven into the soil to the depth of tillage and then inserted a steel plate under the cylinder to permit the removal of the soil in an undisturbed condition. The sample was then transferred to a graded nest of sieves that were shaken by hand and the weights determined. He was able to get good agreement between replications with the few tests made.

Keen (*12*) and his co-workers have used the drawbar pull on tillage implements which they measured with dynamometers to indicate the differences in soil structure. They also used the depth of penetration of a sharpened instrument into the soil under definite impact as a means of measuring the compaction. Davis (*8*) has further perfected this apparatus with a mechanical data recorder, and has used it extensively. Another even simpler and less expensive implement of this type has been designed and used by Culpin (*7*). This instrument also has a self-recording attachment.

The measurement of the porosity of soil by permeability of gases and liquids has been used as a means of studying certain physical properties. Bouyoucos (*3*) has devised a method of measuring water penetration by slaking a definite quantity of soil on a filter paper in a Buchner funnel and then applying suction. Methods of studying permeability by means of various kinds of tubes are too numerous to mention here. Buehrer (*4*) at Arizona has devised a method of passing air through soils under definite conditions of compaction, and using the values thus obtained to define soil structure. Dojarenko (according to Krause, *13*) in Russia has measured the so-called "capillary and noncapillary" pore space as an expression of the soil structure, considering these values to be much more expressive of the physical properties of field soils than volume-weight expressions where the total pore space alone is calculated. The determination of capillary and noncapillary pore space is made by taking a column of soil 10 cm high, setting it on a piece of filter paper that is in contact with a free water surface, and permitting the soil to absorb as

[4] Hoffman, A. H. Unpublished manuscript.

much water as possible in 48 hours. The volume of water retained under these conditions is known as "capillary pore space" and the remainder of the pore space is considered "noncapillary pore space." He designed a special tube 10 cm high with a volume of 100 cc for obtaining samples in an undisturbed state. The principal objection to this measurement is that the amount of water that can be absorbed by any given soil will depend on the height of the column.

EXPERIMENTAL METHODS

Soils.—The soils on which experiments were carried out are of the Yolo, Capay, and Denverton series. These are all mineral secondary soils derived from sedimentary rock sources.

The Yolo soils are recent alluvial soils occupying smooth, gently sloping alluvial fans. There are wide variations in textural types within this series. Normally the surface soils are friable, but they become easily puddled under improper management. The subsoils are loose and friable, and of various textures. Stratification is common in the subsoil. Drainage is adequate and root and water penetration through the soil is excellent.

The soils of the Capay series are closely related to those of the Yolo series but are found further out on the alluvial fans with flatter relief and somewhat restricted drainage. The surface textures are heavy, usually of clay texture, and exhibit an adobe structure. When wet, these soils are very sticky, and when dry, large cracks occur which leave the soil in large hard adobelike blocks. The subsoil is of somewhat heavier texture than the surface soil, and is considerably compacted. This greatly inhibits root and water penetration. During the rainy season, water often stands in pools on the surface for a considerable period of time. As the water disappears from the surface, the surface soil dries rapidly and adobe cracks form, but the subsoil remains saturated for a considerable period of time after the surface soil becomes dry. The water table is often found within 6 feet of the surface in these soils.

The Denverton soils occupy high rolling terraces, often with fairly steep slopes. The profiles are immature to semimature in stage of development. Surface textures are usually heavy clay loams or clays that have definite adobe structures. Unlike those of the Capay soils, however, the adobe blocks have a large number of secondary cracks. This condition renders the surface soil very friable. The large adobe blocks break down readily to small angular units which are fairly stable. The subsoil is somewhat compact yet it is moderately permeable to roots and water. The physical properties of these soils are far more favorable to root and

water penetration and to cultural treatments than the soils of the Capay series. Owing to their irregular relief, however, they are seldom brought under irrigation.

Method of Sampling.—The samples were taken to tillage depth in the case of cultivation tests, and to specified depths in the case of irrigation tests and studies of seasonal variations, by driving a 14-inch steel cylinder into the soil, excavating the soil from around the cylinder, and driving a piece of sheet steel under it to remove the samples without disturbing the structure. The samples thus obtained were carefully transferred to orchard lug boxes and permitted to dry slowly under shelter.

In 1935, the percentages of moisture and the volume weights were obtained at the time the samples were collected.

Volume-Weight Determinations.—During the 1935 season, a method was found for determining the volume weight of the soil as samples were being taken for aggregate analyses. The volume weight was measured by using the same cylinder and sample as was used for sampling for aggregate analysis. After a sample had been removed from the ground as described under "Methods of Sampling," a straight-edge was placed across the top of the tube, and from 75 to 100 measurements, spaced systematically over the surface, were made from this straight edge to the surface of the soil in the cylinder. This permitted calculating the portion of the cylinder unoccupied by the sample. The difference between this figure and the total volume gave the volume of the sample. Aliquot moisture samples were taken in duplicate, from the soil right next to where the sample had been removed, and these were used as the moisture content of the sample in calculating its volume weight. The entire sample was weighed as it was taken from the field, and from the data thus obtained the volume weight was calculated. Replicates agreed within 5 per cent, which is considered good for this type of sampling. In all volume-weight determinations here reported the figures quoted are averages of 4 replicates.

Method of Sifting.—The air-dry samples were sifted in two stages: first through a nest of very coarse sieves, then in a Ro-tap shaker.

The nest of coarse sieves (designed especially for this purpose) is made of wooden boxes 8 inches deep and 2 × 3 feet inside dimensions with rods or pipes to form the sieves, the diameters being proportioned to the size of the opening. The coarsest screen has 1⅛-inch rods set 6 inches apart on center, which gives openings of 4⅞ inches; the next has ¾-inch rods 4 inches apart on center, which gives openings of 3¼ inches; and the third screen has ⅜-inch rods 2 inches apart on center, which gives 1⅝-inch openings. The fourth is a box of the same size with a solid bottom,

in which the material passing through the finest sieve is caught. These are nested in a frame and held in place by dowels. This frame is mounted on wheels which fit on tracks of 2-inch angle iron. The tracks have stops at each end that permit a 24-inch movement of the nest of sieves. These tracks are mounted on rockers, which rock the frame while it is being rolled along the tracks. Twelve shakings of this sieve are sufficient to separate the sample to its various sizes.

The material collected in the solid box of the large shaker was sifted in a Tyler Ro-tap shaker. The sieves have openings of approximately ¾, ⅜, $^3/_{16}$, $^3/_{32}$, $^3/_{64}$, and $^3/_{128}$ inch. The first two are unnumbered, but the last four are 4, 8, 14, and 28 mesh, respectively. The material fine enough to pass through the finest mesh was caught on a solid pan that could be nested with the sieves. As only 3 pounds of soil can be shaken in this machine at one time, a number of determinations were necessary for each sample.

The Ro-tap shaker is operated with an electric motor and has a speed of about 150 shakes a minute. There is a horizontal movement of about 2 inches, and at the same time a vertical displacement of about 1 inch caused by a hammer that bounces the sieves up and down. Fifty shakes were found to be sufficient to sift a sample (see p. 437).

The soil aggregates have irregular shapes, yet they are compared as if they had regular shapes. Since their exact dimensions are not known, the calculation of the surface cannot be made in definite units, but only in relative terms, and so the comparison of surfaces on all the fractions of the sample is called "relative surface" and is expressed in nondimensional units.

In using the relative-surface values as here calculated, two assumptions are made: (1) that aggregates within the same sample of soil have the same volume weight; (2) that the aggregates are cubes.

The value is calculated on the actual size of the sieve opening, which is the minimum size of particles in any size range, except for the fraction which passes through the finest sieve. Here an arbitrary value of one-half that of the finest sieve is used. These minimum values are proportional to the mean values for the size ranges and hence will not affect the ratio for the various sieve openings.

Since the same set of sieves was used for all of the sieve analyses, the value is a constant for any one fraction. The values for these fractions are as follows: through $^3/_{128}$ inch, 416.0; $^3/_{128}$ inch, 208.0; $^3/_{64}$ inch, 104; $^3/_{32}$ inch, 52; $^3/_{16}$ inch, 26; ⅜ inch, 13.0; ¾ inch, 6.5; 1⅝ inches, 3.0; 3¼ inches, 1.56; and 4⅞ inches, 1.0.

The relative-surface values are obtained according to the following formula:

$$RS = \sum \left(\frac{O_1}{O_1} M_1 + \frac{O_1}{O_2} M_2 + \ldots . \frac{O_1}{O_n} M_n \right),$$

where:

RS = relative surface
O_1 = sieve opening of the coarsest sieve
O_2 = sieve opening of the next coarsest sieve
M_1 = per cent of sample retained on the coarsest sieve
M_2 = per cent of sample retained on the next coarsest sieve.

The finest fractions have such a great influence on the values for relative surface that small differences in the percentage values for these finer fractions greatly affect this value, whereas large differences in the coarser fractions do not alter it very much.

Two soils with entirely different size distributions of aggregates may have very close relative-surface values; and, likewise, other soils that have very similar size distribution of particles may have relative-surface values that are not so close. If the percentage values for the three finest fractions are very much alike, the relative-surface values will not be greatly altered by a drastic change in the size distribution of the other seven fractions. In order to get a more complete picture of the changes that occur within any soil, both the figures for the size distribution of aggregates and the values for the relative surface are presented in form of tables, or, where the data on size distribution of aggregates are plotted as curves, the values for the relative surface are given in tabular form with the legend for the curves.

Plotting of Data on Graphs.—Many of the results here presented are plotted on graphs, which afford an easy way of making comparisons. The sieve openings are plotted as abscissas and summation percentages as ordinates. Summation percentages are used instead of the percentages on each sieve because the curves thus plotted are much easier to compare. When curves on the same graph are compared, the curve highest on the graph has the finest aggregates.

In the lower right-hand corner of each graph, the data for the four finest fractions are replotted on a larger scale: the scale for the abscissa is 10 times, and that for the ordinate 2 times, the respective scales on the main graph.

EVALUATION OF THE METHODS USED

Effect of Sifting.—As the term is used in this discussion, a "soil aggregate" is composed of a number of individual soil particles that form a mass sufficiently stable to act as an individual unit.

Many of the clods had rather large cracks as the sample was placed on the large sieve. In most cases, the sifting manipulation was severe enough to break the clods apart at the cracks into aggregate units, but not severe enough to break up uncracked units. Careful observations of the clods on each sieve revealed that very few of them showed any cracks, yet their surfaces did not show fresh breaks, which was taken to indicate that very few aggregate units were broken in this process.

The amount of shaking will obviously affect the results: if inadequate, the sample will not be completely separated; if too prolonged, the aggregates will be broken or worn down.

The data recorded in table 1 show two tests on Sacramento adobe clay with the Ro-tap shaker. The samples were shaken 50 times in the usual manner and the weight on each sieve recorded. The material was reassembled and the process repeated, this time with 200 shakings. The data were again recorded and the process repeated several times, with 250 shakings at each repetition thereafter, until 1,500 in all had been given the samples.

The percentage on the intermediate and finer sieves ($\frac{3}{16}$, $\frac{3}{32}$, $\frac{3}{64}$, and $\frac{3}{128}$ inch) did not change very much. The two coarsest sieves lost some material, and the solid pan gained a little by each successive series of shakings. These results indicate that although there is some wearing down of aggregates by shaking, it is more a case of grinding off corners than breaking down aggregates. A careful examination of the aggregates at the end of this prolonged shaking showed that, especially on the three coarsest sieves, they are well rounded, having almost the appearance of water-worn gravel. These data clearly show that the aggregates are sufficiently stable to be measured in this manner, and that 50 shakes of the Ro-tap are enough to separate the sample properly into the various-sized units.

Variability of Samples.—A certain amount of variability in the samples is to be expected, so that no one determination will convey a true picture of the state of aggregation of any soil. An average of several determinations will more accurately describe this condition, and all of the data presented are averages of four or more replicate samples.

Table 2 shows differences between 8 individual samples on each of three different sets taken in an orchard on Yolo loam as the field was

being cultivated. The first set was taken before any tillage operation, the second after the same strip had been cultivated in one direction with a heavy disk harrow to a depth of 4 inches, and the third after it had been cross-cultivated with the same implement at right angles to the first operation. The cultivations were made on the same day, within a few hours

TABLE 1

PERCENTAGE DISTRIBUTION OF SOIL AGGREGATES AFTER VARIOUS NUMBERS OF SHAKINGS IN THE RO-TAP SHAKER

Number of shakings	Sieve opening							Total
	Through 3/128 inch	3/128 inch	3/64 inch	3/32 inch	3/16 inch	3/8 inch	3/4 inch	
First test								
50	15.1	13.0	18.1	17.5	16.5	16.7	2.9	99.8
250	16.8	13.5	18.7	17.3	16.5	14.0	2.7	99.5
500	17.5	13.9	19.2	17.5	16.0	13.7	1.8	99.6
750	18.1	14.0	19.2	17.9	16.0	12.5	1.8	99.5
1,000	18.6	14.1	19.6	17.9	15.8	11.7	1.8	99.5
1,250	18.9	14.3	19.6	18.0	15.7	11.2	1.8	99.5
1,500	19.4	14.3	19.7	18.0	15.5	12.0	0.8	99.7
Second test								
50	15.8	12.3	16.9	16.0	16.4	19.6	2.9	99.9
250	17.5	12.8	17.1	16.3	15.8	17.6	1.9	100.0
500	18.0	12.8	17.4	16.5	15.5	17.4	1.9	99.5
750	18.7	12.8	17.4	16.5	15.8	16.7	1.7	99.5
1,000	19.2	13.1	17.4	16.6	15.3	16.2	1.0	98.8
1,250	19.5	13.2	17.4	16.8	15.6	15.1	1.0	98.6
1,500	20.1	13.1	17.6	16.9	15.5	14.4	1.0	98.6

of each other, and all of the samples were taken within an area about 20 feet square.

Definite pulverizing effect is obtained by each tillage operation, yet there is considerable variation between individual samples for each treatment. There is usually a greater variability in the coarser fractions than in the intermediate and finer fractions. Some variability may be ascribed to the method of making the determinations, but much more of it is due to the natural heterogeneity of the soil, so that an average of a number of replicate samples for the same treatment is the only safe way of making comparisons between different cultural treatments.

Comparison of Moist and Air-dry Sifting.—Keen (*12*) and Hoffman[5] sifted their samples as they were taken from the field. In the present study, because comparisons were to be made between samples taken from

[5] Hoffman, A. H. Unpublished manuscript.

fields under variable conditions of texture and moisture, and also at different seasons, it was desirable to bring the samples to moisture conditions as nearly comparable as possible. The air-dry state is most convenient, even though this necessitates storing the samples while drying.

TABLE 2

VARIABILITY IN PERCENTAGE DISTRIBUTION OF SOIL AGGREGATES IN INDIVIDUAL SAMPLES OF YOLO LOAM

Sample No.	Sieve opening										Relative surface
	Through 3/128 inch	3/128 inch	3/64 inch	3/32 inch	3/16 inch	3/8 inch	3/4 inch	1⅝ inches	3¼ inches	4⅞ inches	
					No cultivation						
1	5.0	1.8	2.5	3.7	5.5	9.1	14.2	24.1	24.8	9.5	3,380
2	3.9	1.4	2.2	3.3	5.1	8.2	12.5	18.4	10.6	34.3	2,741
3	4.8	1.7	2.5	3.9	5.3	8.0	12 0	17.4	27.5	16.5	3,243
4	4.2	1.3	2.0	3.4	6.0	10.9	18.4	20.2	21.2	12.4	2,935
5	5.8	1.7	2.4	3.7	5.6	9.6	11.4	31.7	28.2	0.0	3,694
6	7.4	1.9	2.8	4.3	6.5	10.6	14.6	30.7	12.1	8.9	4,513
7	6.6	1.9	2.9	4.5	6.8	10.3	13.1	28.1	17.8	8.2	4,191
8	4.5	1.4	2.0	3.2	4.9	7.4	11.9	16.5	19.0	29.3	2,947
Av.	5.3	1.6	2.4	3.8	5.7	9.3	13.5	23.4	20.2	14.9	3,460
					Cultivated one way						
9	10.9	3.3	4.7	6.8	9.2	13.0	15.8	20.7	15.5	0.0	6,656
10	9.6	3.2	4.7	7.5	10.3	15.9	22.6	26.4	0.0	0.0	6,242
11	14.3	4.1	5.1	8.0	14.3	18.2	20.2	11.6	4.2	0.0	8,570
12	12.1	3.7	5.3	7.4	11.1	15.5	18.2	16.1	10.3	0.0	7,390
13	12.6	3.0	4.3	6.7	9.9	13.7	17.8	27.9	4.2	0.0	7,290
14	12.7	3.4	4.3	6.0	8.7	12.1	15.9	14.0	22.8	0.0	7,300
15	10.2	3.2	5.1	8.2	11.4	15.2	19.3	18.5	9.0	0.0	6,551
16	11.3	2.9	4.4	7.0	11.2	15.7	26.1	22.2	0.0	0.0	6,857
Av.	11.7	3.4	4.7	7.2	10.8	14.9	19.5	19.7	8.3	0.0	7,113
					Cultivated 2 ways						
17	17.7	5.6	8.1	11.7	14.7	17.9	14.6	9.8	0.0	0.0	10,724
18	12.7	4.6	6.7	10.0	13.6	17.8	22.4	13.2	0.0	0.0	8,285
19	16.9	5.4	7.2	10.1	13.6	17.4	17.8	11.6	0.0	0.0	10,158
20	14.2	4.8	6.8	9.0	13.0	17.1	25.4	9.5	0.0	0.0	8,829
21	23.1	5.8	7.3	9.6	11.7	13.5	13.7	12.9	2.2	0.0	12,678
22	15.3	5.7	8.3	12.5	17.9	20.9	15.4	3.7	0.0	0.0	9,986
23	14.5	5.9	8.2	11.0	13.6	16.0	15.1	12.2	2.5	0.0	9,393
24	18.6	7.0	8.9	11.3	13.5	16.2	15.8	4.7	4.1	0.0	11,393
Av.	16.6	5.6	7.7	10.7	14.0	17.1	17.5	9.7	1.1	0.0	10,203

A few tests were made to compare samples sifted at field moisture content and under air-dry conditions. The data (table 3) for samples from fields of Yolo loam and of Yolo silt loam are presented to show the

differences in samples taken at the same time, one set sifted immediately after sampling, and the other air-dried before sifting. Replicate samples agreed well when sifted moist as well as when sifted in the air-dry state. There were marked differences in the size distribution under these two systems of handling the samples. The amounts both of very coarse material and of fine material were always greater when sifted in the air-dry condition.

At field moisture content, the larger aggregates seem to have been weak enough to be broken by the amount of agitation necessary for complete separation with this apparatus. On the other hand, there was less material fine enough to pass through the finest sieve. The moisture films undoubtedly held the dust particles together in aggregates sufficiently stable to prevent their passing through the finest sieve on the Ro-tap shaker. In two respects, therefore, size distribution of aggregates as found by sifting the samples at their field moisture content is obviously different from that of the samples when taken from the field.

TABLE 3

PERCENTAGE DISTRIBUTION OF SIZE AGGREGATES SIFTED AIR-DRY AND AT FIELD MOISTURE CONTENT

Soil and plot No.	Per cent of water	Sieve opening										Relative surface
		Through 3/128 inch	3/128 inch	3/64 inch	3/32 inch	3/16 inch	3/8 inch	3/4 inch	1⅝ inches	3¼ inches	4⅞ inches	
Yolo loam												
Plot 1	3.42	5.4	3.5	4.6	6.2	8.5	12.2	15.0	23.0	17.6	4.3	4,362
	20.9	1.6	7.3	12.2	11.4	13.9	17.3	18.1	13.8	4.9	0.0	4,791
Plot 2	3.06	6.2	3.7	4.8	6.2	8.3	11.3	14.3	23.5	21.6	0.0	4,718
	20.1	2.0	7.3	11.6	10.7	13.0	16.4	17.2	19.8	2.0	0.0	4,805
Plot 3	3.30	3.5	2.0	3.0	4.1	6.0	9.7	15.6	25.1	26.2	4.7	2,936
	21.5	0.3	3.3	9.5	9.4	11.5	15.9	18.3	25.5	6.3	0.0	2,993
Yolo silt loam												
Plot 1	3.10	6.5	2.5	3.0	4.3	6.5	10.1	14.1	27.3	19.9	6.2	4,259
	21.9	4.2	6.6	8.7	9.0	11.7	15.8	19.9	20.5	3.3	0.0	5,202
Plot 2	3.25	6.8	2.6	3.2	4.4	6.3	9.6	14.6	25.9	14.4	12.3	4,436
	21.7	3.4	8.5	11.3	11.0	13.4	17.6	19.3	14.1	1.4	0.0	4,632
Plot 3	3.18	3.8	2.3	3.1	4.4	6.6	10.5	15.4	24.3	23.7	6.0	3,124
	21.7	0.8	5.3	7.5	8.4	11.2	14.4	15.8	26.9	9.7	0.0	3,350

With the air-dry samples, on the contrary, the stability previously demonstrated (p. 437) for the air-dry aggregates indicates that the size distribution as found by sifting was essentially the same as that before sifting. It may be argued that there is a possibility for change in the size

of the aggregates as the samples dry out, but this phase was not investigated.

The relative-surface values under the two different sets of conditions are not greatly different.

For comparison of the degree of wetness of the various samples, the ratio of the moisture content to the moisture equivalent at the time of sifting is given in table 4. These soils were all sampled the same length of time after a series of irrigations, and were very close in their degree of wetness and actual moisture content.

TABLE 4

Ratio of Percentage of Water at Field Capacity to Moisture Equivalent in Yolo Loam and Yolo Silt Loam

Soil and location	Per cent moisture	Moisture equivalent	$\frac{\text{Per cent } H_2O}{\text{M.E.}} \times 100$
Yolo loam			
Plot 1	20.9	25.15	0.83
Plot 2	20.1	25.30	0.79
Plot 3	21.5	25.88	0.83
Yolo silt loam			
Plot 1	21.9	25.95	0.84
Plot 2	21.7	26.42	0.82
Plot 3	21.7	26.80	0.81

EFFECT OF TILLAGE ON MACROSTRUCTURE

Orchards.—Permanent crops, such as orchards and vineyards, are usually subjected to tillage operations for the purposes of turning under covercrops or destroying weeds. Usually this is done with disks of some type, either single or double, and the depth of penetration of the implement is rather shallow, 3 to 6 inches being the most common. In the present study, the implement was a heavy single-disk harrow, operated at depths of 4 to 5 inches. The second cultivation, when given, was at right angles to the first.

Table 5 gives the data for orchards on the Yolo series. In all cases, each tillage operation had a distinct pulverizing effect.

Yolo loam was sampled in three locations (table 5, plots 100, 200, and 300), and considerable variation was found in the size distribution at each location before any tillage operation was performed. In each case, there was a distinct pulverizing effect by each operation, but the intensity of this effect was variable.

The two locations on the Yolo clay loam (plots 400 and 500) were not

so variable before tillage, and the pulverizing effect of the tillage was also a little more uniform.

The soils with the coarser textures were less aggregated than those of the finer textures. Before tillage, Yolo fine sandy loam (plot 000) showed a much finer condition of aggregates than the other two soils. It had relative-surface values two or three times as great as the loam and five or six times as great as the clay loam.

TABLE 5

PERCENTAGE DISTRIBUTION OF SOIL AGGREGATES FROM DIFFERENT LOCATIONS AND SOIL TYPES IN AN ORCHARD

Plot No.	Cultivations	Sieve opening: Through 3/128 inch	3/128 inch	3/64 inch	3/32 inch	3/16 inch	3/8 inch	3/4 inch	1⅝ inches	3¼ inches	4⅞ inches	Relative surface
Yolo fine sandy loam: percentage distribution of aggregates												
000	0	21.8	3.8	4.6	6.6	8.9	10.1	9.0	12.5	5.0	17.7	11,157
	1	23.8	4.5	5.6	8.2	11.2	14.3	13.9	13.4	5.2	0.0	12,411
	2	29.7	5.9	7.1	9.7	12.2	13.5	11.6	10.6	0.0	0.0	15,420
Yolo loam: percentage distribution of aggregates												
100	0	7.2	2.0	2.6	3.7	5.4	7.3	9.5	17.8	12.7	31.8	4.273
	1	12.9	3.2	4.5	6.4	9.0	12.5	15.5	20.5	7.7	7.9	7,406
	2	14.7	4.0	5.5	7.6	10.3	13.6	14.7	17.7	4.9	6.9	8,506
200	0	5.8	1.7	2.1	3.3	4.5	6.7	9.8	16.1	12.7	37.2	3,506
	1	10.9	2.8	3.7	5.1	7.0	9.6	10.8	20.0	19.9	10.2	6,240
	2	23.6	7.6	8.6	10.0	12.7	13.8	12.4	9.9	1.6	0.0	13,435
300	0	12.2	2.9	3.5	4.5	7.1	10.4	13.3	17.5	19.2	9.3	6,778
	1	15.6	4.3	4.4	5.7	7.5	11.2	13.0	19.1	7.4	12.2	8,333
	2	19.5	4.7	5.3	7.1	9.4	14.0	16.2	14.6	9.5	0.0	10,597
Yolo clay loam: percentage distribution of aggregates												
400	0	2.3	1.3	1.9	2.7	4.1	6.2	8.4	12.5	22.5	38.1	1,916
	1	8.9	5.6	6.8	8.9	11.9	15.3	16.8	17.2	8.8	0.0	6,718
	2	13.0	7.1	8.7	10.7	13.5	15.9	14.8	13.1	3.2	0.0	9,025
500	0	2.6	1.6	2.2	3.2	4.6	6.8	8.0	10.9	19.4	40.6	2,175
	1	8.0	5.1	6.3	8.5	11.9	15.3	18.8	21.7	4.3	0.0	6,185
	2	10.4	6.5	7.4	9.0	11.5	14.5	15.1	19.2	6.5	0.0	7,563

Table 6 shows the results of two seasons' studies on tillage in an orchard on Denverton adobe clay. During the 1933 season, there was no noticeable pulverizing effect due to the tillage operations, whereas there was a slight pulverizing effect after the second cultivation in the 1934 season. The soil was in a more cloddy condition in 1934 than in 1935.

Despite its heavy texture, this soil showed a good granular structure. The soil cracks into large adobe blocks on drying out, but these large blocks have numerous secondary cracks that break the soil into rather small irregular-shaped clods that are themselves rather firm; hence, the tillage operation did not have a very strong pulverizing effect.

In order to compare more closely the size distribution of aggregates after the various treatments, the data from one set of samples from Yolo loam and one set from the Denverton adobe clay are plotted on graphs.

TABLE 6

Percentage Distribution of Size Aggregates before and after Tillage Operations in an Orchard on Denverton Adobe Clay, 1933 and 1934

Year	Cultivations	Sieve opening										Relative surface
		Through 3/128 inch	3/128 inch	3/64 inch	3/32 inch	3/16 inch	3/8 inch	3/4 inch	1⅝ inches	3¼ inches	3⅞ inches	
1933	0	13.9	13.3	15.2	14.6	14.4	12.3	7.7	7.3	1.4	0.0	11,510
	1	15.5	14.3	16.0	15.0	15.0	12.9	7.1	4.2	0.0	0.0	12,483
	2*	14.7	12.3	13.2	12.8	13.7	14.6	11.5	7.2	0.0	0.0	11,363
	After rain	13.8	12.6	14.0	13.6	14.6	14.3	11.6	5.6	0.0	0.0	11,159
1934	0	7.0	8.9	11.0	10.2	13.4	14.8	12.1	25.1	0.0	0.0	7,108
	1	7.3	9.2	12.1	12.4	14.1	16.3	28.5	0.0	0.0	0.0	7,622
	2*	10.7	11.8	15.4	13.9	14.1	15.6	18.5	0.0	0.0	0.0	9,895

* Second cultivation at right angles to first.

Figure 1 gives the data for plot 300 on Yolo loam and shows the distinct pulverizing effect of each cultivation. The curves have similar shapes. The differences are also manifest in the relative-surface values.

Figure 2 shows the curves for the 1933 samplings on Denverton adobe clay. The size distribution of aggregates in these samples was not greatly altered by the cultural treatments. These curves occur much higher on the graph than those of the Yolo loam, which shows them to have finer aggregates. The curves are very close together and of similar shape. Curve *B*, after cultivation in one direction, is slightly higher than the other curves on this graph. This difference is also manifest in the relative-surface values. The other three curves cross each other a number of times and are very close together throughout the entire range of the curve. Their relative-surface values are also very close.

Seedbed for Beans.—In 1933 and 1934 a number of studies were carried out on a private farm in the vicinity of Davis, California. The studies were made on the size distribution of aggregates after different tillage operations in preparing seedbeds. This farm is composed mainly of soils of the Yolo series, ranging in texture from fine sandy loam to clay loam, but there is also a body of Capay adobe clay on this farm.

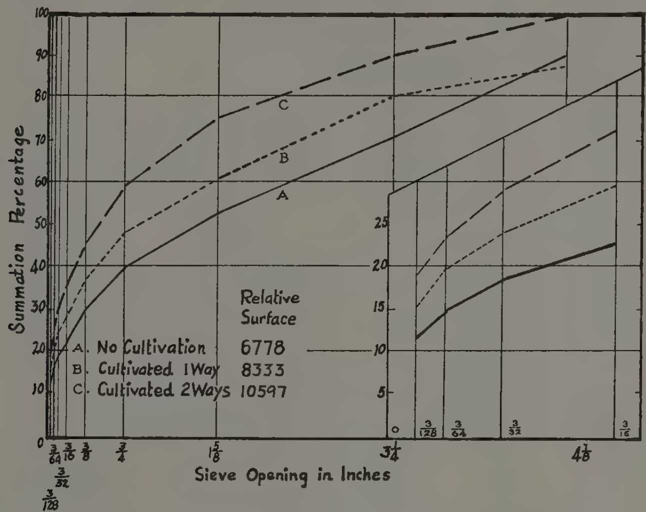

Fig. 1.—Size distribution of aggregates before and after tillage operations in an orchard (plot 300) on Yolo loam soil, 1933.

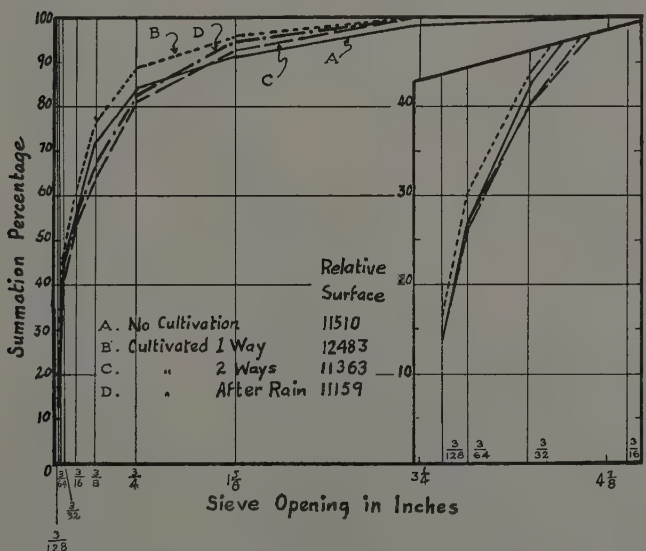

Fig. 2.—Size distribution of aggregates before and after tillage operations in an orchard on Denverton adobe clay, 1933.

The farm had been used for dry-land grain for a good many years. For four or five years previous to these investigations, the entire farm had been in sod and pastured to sheep.

In 1934 a field of considerable size was planted to beans. Two areas were selected for the investigations on the preparation of the seedbed: one area was on Yolo clay loam and the other on Capay adobe clay.

The bean field was worked as a unit, and the treatments on the whole field were the same. These were briefly as follows: The field was plowed in a fairly dry condition, to a depth of 6 inches. Some leveling was done next by use of a heavy float and a large scraper. After this, the field was preirrigated, permitted to dry at the surface for nearly a month, then harrowed with a spring-tooth harrow, and finally rolled with a cultipacker before seeding. The leveling work on this field did not necessitate the moving of very much soil except for small localized areas. No soil was moved to or from the areas in either sampling location.

All of the data for the studies of preparation of seedbed on this farm are plotted in graphs. Figure 3 shows the results of the treatments on Yolo clay loam and figure 4 shows those for Capay adobe clay. On the Yolo clay loam, the plowing had only a very slight pulverizing effect, but the same treatment had a very definite pulverizing effect on the Capay adobe clay. On both plots, the leveling operations had a very strong pulverizing effect, and the plots were in their most finely pulverized state after this treatment. After the preirrigation and subsequent drying period, both plots were far more cloddy than they had been before they had received any cultural treatment. On both plots, the harrowing with a spring-tooth harrow and rolling with a cultipacker had some pulverizing effect. The curves for the data on the Yolo clay loam (fig. 3) are of very similar shape. The three curves *A*, *B*, and *F* are close together, yet the corresponding relative-surface values are 4,940, 5,348, and 5,648, respectively. As previously noted, small changes in the percentage of the finer fractions cause large changes in these values. Curve *F* falls between curves *A* and *B* throughout most of its length, but the percentage of very fine fractions is higher in *F*, as shown on the enlargement at the lower right-hand corner of figure 3.

The similarity of curves *A* and *F* indicates that, for this soil, the size distribution of aggregates was practically no different when the field was seeded than it had been before plowing. The actual physical condition of the field, however, was greatly altered. The soil was dry and compact and in a fairly heavy sod before plowing. As the field was finally fitted before seeding, it was loose and friable and the sod had all been broken up. Unfortunately no volume-weight measurements were taken this season.

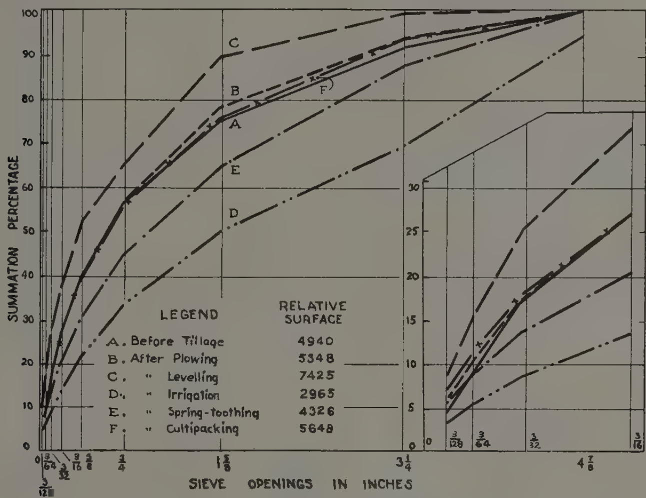

Fig. 3.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for beans on Yolo clay loam, 1934.

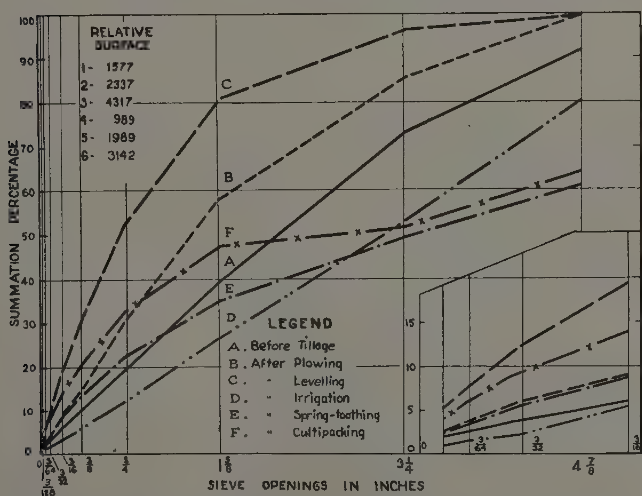

Fig. 4.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for beans on Capay adobe clay, 1934.

The curves in figure 4 for Capay adobe clay are spread wider apart than those in figure 3. Curves E and F in this figure do not have the same general shape as the others. The field was permitted to dry for several weeks after irrigation. The Capay soils have very sluggish drainage, and water stood on this area several days longer than on the Yolo clay loam. As the field dried out after the water disappeared from the surface, a definite crust about 2 inches thick was formed; below this, the soil was very wet. The field was in this condition when the spring-tooth harrowing and cultipacking were done. In both instances, samples were taken to 4-inch depths. Harrowing increased the amount of fine material over that of the sample before any tillage was done, but also increased the amount of coarse material. The drier soil at the surface was somewhat crumbled, but the pressure of the implement caused the very wet soil under the crust to be pressed together, and this dried out into very coarse lumps. The subsequent rolling with the cultipacker had a rather strong pulverizing effect on the crust but did not affect the lower portion of this layer. Here again, the strong influence of the finer fractions is clearly shown. Curve A is above curve E for most of its length but somewhat below the latter at the beginning; yet it has a relative-surface value of 1,577 as compared to that of 1,989 for curve E. Curve F has a relative-surface value of 3,142, which is just double that for curve A; yet it lies above curve A for only about half its length and falls far below for the last half.

The size-distribution curves and relative-surface values show the Yolo clay loam to have much less cloddy structure than the Capay adobe clay.

Seedbed for Sugar Beets.—In 1935 on this same farm two fields were being prepared for sugar beets. The smaller field was nearly all Yolo clay loam; the larger field had two textural types, Yolo loam and Yolo fine sandy loam. Representative areas of each of the three types were selected, and samples were taken after each tillage operation. Volume-weight determinations were made as the samples were taken. The two fields were not worked simultaneously, and the treatments were not exactly alike. The areas of loam and fine sandy loam, however, were worked in one unit, and so these two types can be readily compared. The data for the loam texture are shown in figure 5 and those for the fine sandy loam in figure 6.

On this field, the plowing was done with moldboard plows, and a small amount of leveling was done by a large, heavy, wooden float. The disking and harrowing were done in one operation with a spike-tooth harrow attached behind a double-disk harrow. After harrowing, the field was seeded and then rolled with a cultipacker.

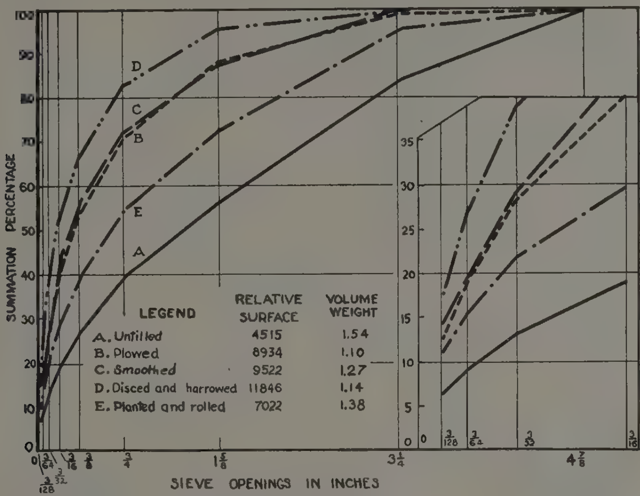

Fig. 5.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for sugar beets on Yolo loam, 1935.

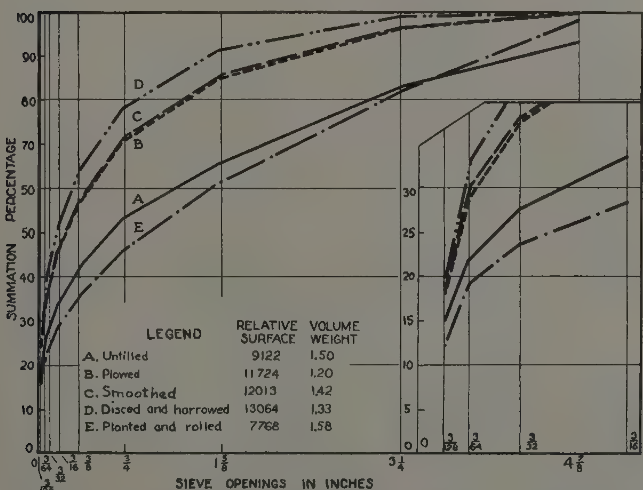

Fig. 6.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for sugar beets on Yolo fine sandy loam, 1935.

On both of these types, plowing had a very pronounced pulverizing effect and also a definite loosening effect. The curves for the plowing treatment lie above those for the soil before tilling in both cases, and there was a definite decrease in the volume weight of the soil: the Yolo loam decreased in volume weight from 1.54 to 1.10 and the fine sandy loam from 1.50 to 1.20, after plowing.

Although, with both types, the relative-surface values were slightly higher after the use of the float, no appreciable change in the size distri-

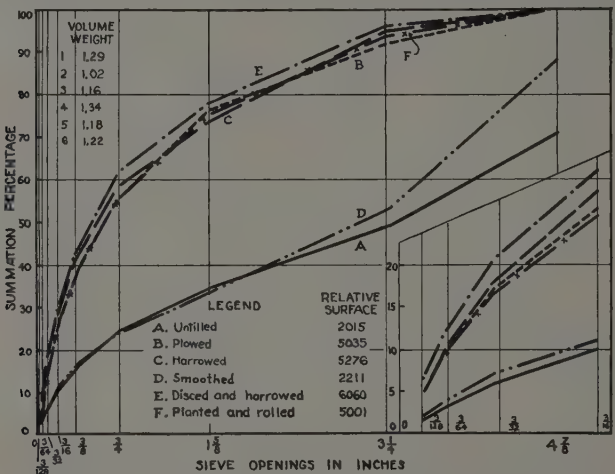

Fig. 7.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for sugar beets on Yolo clay loam, 1935.

bution of aggregates occurred: curves *B* and *C* are almost identical throughout their length, both in figure 5 and in figure 6. On the other hand, the use of the float had a very pronounced effect in compacting the soil, as shown by the increases in the volume weights. On both types, the harrowing had a decided pulverizing and loosening effect. Volume weight decreased very definitely: in the case of the Yolo loam, it was reduced almost to that after plowing.

The planting and rolling in both instances increased the cloddiness and the volume weights. On the loam texture, the soil was somewhat more pulverized than before plowing, and the volume weight somewhat less. On the fine sandy loam, however, the soil was a little more cloddy and a little more compact after the final operation than before any tillage was performed.

The field of Yolo clay loam on the same farm, also being prepared for sowing sugar beets, was tilled a little later, and during the process there were a number of storms, which slightly altered the procedure on this field. Furthermore, this field was still in sod, whereas the other field on the loam and fine sandy loam types had been in a cultivated crop the year before. After plowing, this field was harrowed with a spike-tooth harrow to further break up the sod before it was worked with the float, so that this field had one more tillage operation than the other. The results on

TABLE 7

MOISTURE CONDITION OF SOILS OF THE YOLO SERIES AS TILLAGE OPERATIONS WERE PERFORMED IN PREPARATION OF SEEDBED FOR SUGAR BEETS, 1935

Treatment	Yolo loam (M.E., 20.13)		Yolo fine sandy loam (M.E., 18.78)		Yolo clay loam (M.E., 26.58)	
	Per cent H_2O	Per cent $\frac{H_2O}{M.E.} \times 100$	Per cent H_2O	Per cent $\frac{H_2O}{M.E.} \times 100$	Per cent H_2O	Per cent $\frac{H_2O}{M.E.} \times 100$
Untilled	19.3	94.8	14.7	78.2	23.5	89.4
Plowed	17.3	84.8	12.8	68.1	17.6	64.3
Harrowed	....	....	....	....	20.0	75.2
Smoothed	16.4	80.5	11.0	58.5	23.1	86.9
Disked and harrowed	16.1	79.1	11.2	59.7	16.2	61.0
Rolled and planted	16.1	79.1	11.1	59.1	15.0	56.4

the size distribution of aggregates and volume weights, and the relative-surface values, are given in figure 7.

Plowing had a very marked pulverizing effect on this soil (curves *A* and *B*, fig. 7), but subsequent harrowing had no further effect, for the curves (*B* and *C*) are almost coincident throughout their length, although the relative-surface value is slightly higher after harrowing. The plowing here caused a distinct decrease in the volume weight, but the harrowing had a slight compacting effect. The subsequent use of the float increased both the cloddiness and the volume weight; in fact, the volume weight was greater than before plowing, despite the fact that the field had previously been in pasture to sheep for a number of years. The increase in cloddiness brought about by the use of the float was caused by the wetness of the field when this operation was performed. Table 7 gives the moisture conditions of the three soil types on this farm at the time of sampling.

The Yolo clay loam had been given considerable time to dry out after the use of the float, so that when the field was disked and harrowed, it was at a very favorable moisture content for tillage operations. This operation (fig. 7, curve *E*) had a distinct pulverizing effect, and the field

at this time was in its most finely pulverized condition. The planting and rolling operations increased the cloddiness only slightly. Disking and harrowing reduced the volume weight somewhat, but the subsequent planting and rolling altered it only slightly. This field, after final fitting and planting, was in a more pulverized condition than before treatment; the volume weight was only a little lower.

Seedbed for Alfalfa.—In 1934 a number of small plots were worked up for seeding alfalfa on the University Farm at Davis, California. After

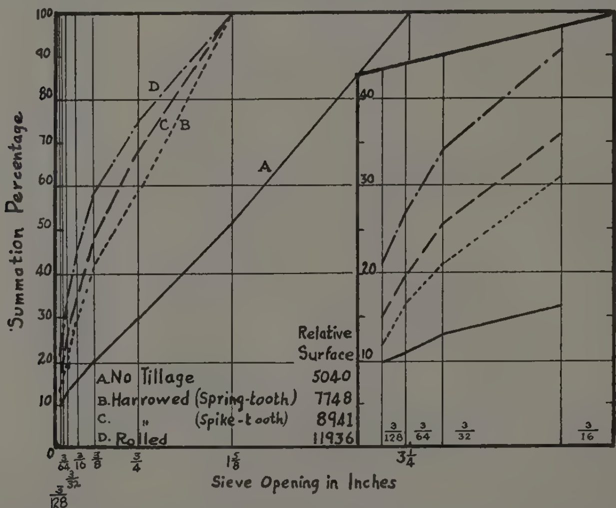

Fig. 8.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for alfalfa on Yolo loam, plot D–15, 1934.

the seedbeds had all been prepared, but before they were seeded, there was a period of heavy rains. After the rains, the surface of the plots crusted over and had to be reworked. Samples were obtained from three of these plots, all on Yolo loam, as the tillage operations were being performed to reprepare the seedbeds. Since the plots here were very small, an 8-inch sampling cylinder was used instead of the 14-inch cylinder that had been used on the other samplings.

Three implements were used in working these plots for seeding. They were first worked with a spring-tooth harrow, then with a spike-tooth harrow, and finally with a spike-tooth roller. The data are plotted on figures 8, 9, and 10. Two of the three plots behaved very much alike (figs. 8 and 9). In these two plots, each tillage operation had a distinct pulver-

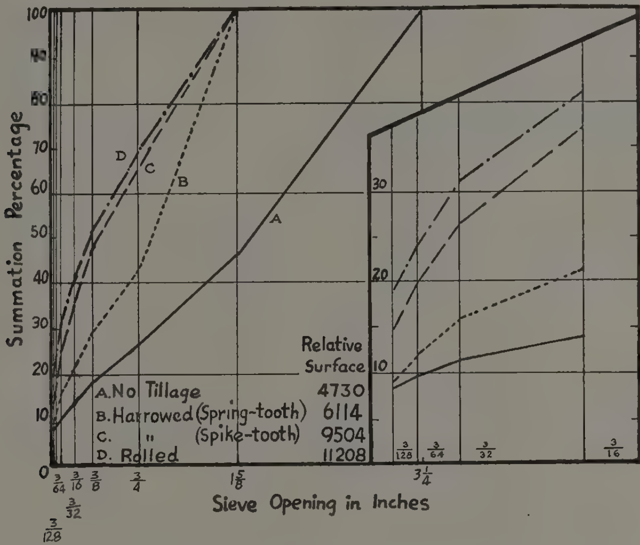

Fig. 9.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for alfalfa on Yolo loam, plot D–25, 1934.

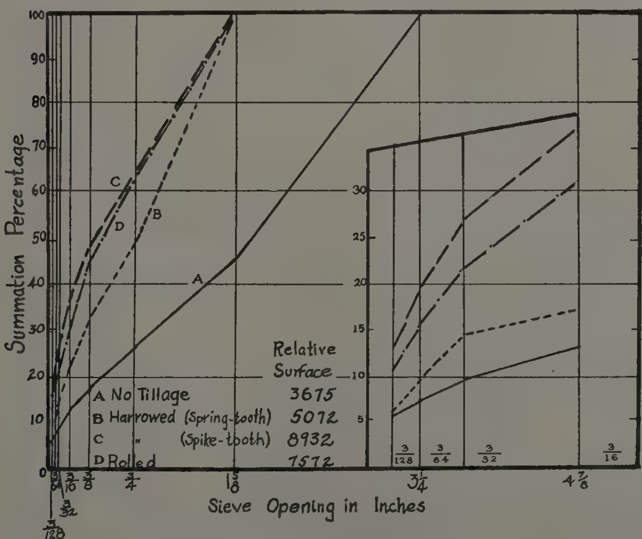

Fig. 10.—Size distribution of aggregates before and after tillage operations in preparation of seedbed for alfalfa on Yolo loam, plot D–35, 1934.

izing effect, although the intensity of the effect was somewhat different: on plot D–15 (fig. 8) the spring-tooth harrow had a greater pulverizing effect than the spike-tooth harrow, whereas the pulverizing effect for these two implements was about the same on plot D–25 (fig. 9). Plot D–35 (fig. 10) is very similar to plot D–25 in the pulverizing effect of the dif-

TABLE 8

Dates of Treatments and Sampling on Yolo Loam Plots for Special Study

	1933			1934			1935		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
Plowed	....	3/4*	2/18*	....	6/7*	5/17*	....	....	....
Harrowed	....	4/3	4/3	....	6/15	6/15	....	....	....
Irrigated 1st series	4/11 4/14 4/17 4/20	4/11 4/14 4/17 4/20	4/11 4/14 4/17 4/20	5/1 5/2 5/3 5/4	5/1 5/2 5/3 5/4	5/1 5/2 5/3 5/4	.... 4/30	.... 4/30	.... 4/30 ....
2nd series	5/11 5/12 5/13 5/15 5/16	5/11 5/12 5/13 5/15 5/16	5/11 5/12 5/13 5/15 5/16	7/3 7/5 7/6	7/3 7/5 7/6	7/3 7/5 7/6	....	....	....
3rd series	7/24 7/25 7/26	7/24 7/25 7/26	7/24 7/25 7/26	....	....	....	....	....	....
4th series	12/1	12/1	12/1	....	....	....	....	....	....
Sampled	3/4 5/4 12/1	3/4 4/3 5/4 12/1	3/4 4/3 5/4 12/1	5/19 7/25	5/18 6/11 6/15 7/26	5/14 6/11 6/15 7/26	4/30 6/3	4/30 6/3	4/30 6/3 ....

* Moisture content when plowed: 1933, plot 2, 20.0 per cent; plot 3, 25.4 per cent; 1934, plot 2, 16.1 per cent; plot 3, 23.2 per cent.

ferent harrows. The rolling had a distinct pulverizing effect on plots D–15 and D–25, but the cloddiness on plot D–35 was increased somewhat by this operation. This plot was in a slight depression and had a higher moisture content when worked, which undoubtedly accounts for the increased cloddiness caused by rolling.

The relative-surface values are given with the legend on each figure. In some instances two curves may appear very close together, yet there will be fairly wide differences in their relative-surface values—compare, for example, curves and relative-surface values for spike-tooth harrowing and for rolling, in figures 9 and 10. In each case, the sample with the higher relative-surface value has the greater percentage of the finer frac-

tions. This is shown in the enlargements of this portion of the curve in the lower right-hand corner of each figure.

Tillage Operations at Different Moisture Contents.—A number of samplings were taken for size distribution of aggregate studies after plowing, harrowing, and irrigation treatments on two sets of plots on the

TABLE 9

DATES OF TREATMENTS AND SAMPLING ON YOLO SILT LOAM PLOTS FOR SPECIAL STUDY

	1933			1934			1935		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
Plowed	....	3/4*	2/18*	....	6/7*	5/17*	....	....	....
Harrowed	....	4/3	4/3	....	6/15	6/15	....	....	....
Irrigated 1st series	4/4	4/4	4/4	5/1	5/1	5/1	5/1	5/12	5/1
	4/5	4/5	4/5	5/2	5/2	5/2	....	....	....
	4/10	4/10	4/10	5/3	5/3	5/3	....	....	....
	....	....	....	5/4	5/4	5/4	....	....	....
2nd series	5/12	5/12	5/12	7/3	7/3	7/3	....	....	....
	5/15	5/15	5/15	7/5	7/5	7/5	....	....	....
	5/16	5/16	5/16	7/6	7/6	7/6	....	....	....
3rd series	7/26	7/26	7/26	....	....	....	....	....	....
	7/27	7/27	7/27	....	....	....	....	....	....
	7/28	7/28	7/28	....	....	....	....	....	....
Sampled	3/25	3/25	3/25	5/19	5/22	5/15	5/1	5/1	5/1
	....	4/3	4/3	7/26	6/11	6/11	6/3	6/3	6/3
	5/4	5/4	5/4	....	6/15	6/15	....	....	....
	12/2	12/2	12/2	....	7/26	7/26	....	....	....

* Moisture content when plowed: 1933, plot 2, 20.0 per cent; plot 3, 24.5 per cent; 1934, plot 2, 17.6 per cent; plot 3, 23.2 per cent.

University Farm that were laid out for water-penetration studies as affected by tillage at different moisture contents. The moisture-penetration studies were made in coöperation with N. E. Edlefsen of the Division of Irrigation Investigations and Practice; the results of these will not be reported here. The two sets of plots were located on Yolo loam and Yolo silt loam, and there were three plots in each set. One plot received no tillage, one was plowed at what was considered a favorable moisture content for plowing, and the other was plowed at moisture contents that were considered too high to obtain the most favorable results from tillage (see footnote, tables 8 and 9). Both of the plowed plots were harrowed lightly after they had been plowed. The plots were 45 × 90 feet and were plowed with a two-horse plow in one direction only, so as not to produce a back furrow in the center of each plot.

After the tillage operations had been completed on both plots in each

set, all three plots were seeded to barley, primarily to keep out weeds. One to four series of irrigations were made on each plot (tables 8 and 9), and the rate of penetration of water into the soil was determined. After each tillage operation, the two tilled plots in each set were sampled; and after some of the series of irrigations, all of the plots in each set were sampled. Samples were taken to 7-inch depths and in 4 replicates. Each sampling removes considerable soil, so that sampling for size distribution of aggregates could not be done after each series of irrigations for fear of altering the rate of water penetration. Tables 8 and 9 give dates of treatments and sampling on these two sets of plots. During the 1934 season, because of conditions which could not be controlled, the plowing was not done until fairly late on these plots, so that before any cultural treatments were made, all plots were subjected to a series of irrigations.

The results of the samplings on these areas are given in the form of graphs similar to those previously presented. For convenience in discussing the graphs, the plots of each set are numbered as follows: plot 1 received no tillage, plot 2 was plowed at favorable moisture content, and plot 3 was plowed while too wet. Figures 11 and 12 give the results on plots 2 and 3 for the 1933 season and figures 13 and 14 for the same plots for the 1934 season.[6]

The plowing (fig. 11) had a definite pulverizing effect on plot 2, which was plowed at a favorable moisture content; but plot 3, which was plowed too wet, was more cloddy after plowing than it had been originally. The plowing in the latter case was done when the soil was too wet to scour off the plowshare. The soil seemed to push up in front of the plow and was thus compacted, which increased the cloddiness. Harrowing had no pulverizing effect on the area plowed at suitable moisture content, in fact, the curve showing the result of this treatment falls slightly below that for plowing (fig. 11, curves *B* and *C*). This slight difference is probably due to the natural heterogeneity of the soil rather than to any effect of tillage. On the plot that was plowed too wet, some pulverizing of the soil, mostly increasing the finer fraction, was caused by harrowing. The amount of coarse material is about the same, but the increase in the fine material accounts for the increase in the relative-surface value (fig. 11, curves *D* and *E*).

For the same season, on Yolo silt loam (fig. 12), the plowing had a definite pulverizing effect on both areas, but the action was more pro-

[6] In order to reduce the number of samplings on plots 2 and 3, they were not sampled before plowing, but the sampling on plot 1 taken at that time is used for these plots. Since the areas are fairly uniform and the plots are small, these results are probably very close to what would have been obtained for the other plots had they been sampled at this time.

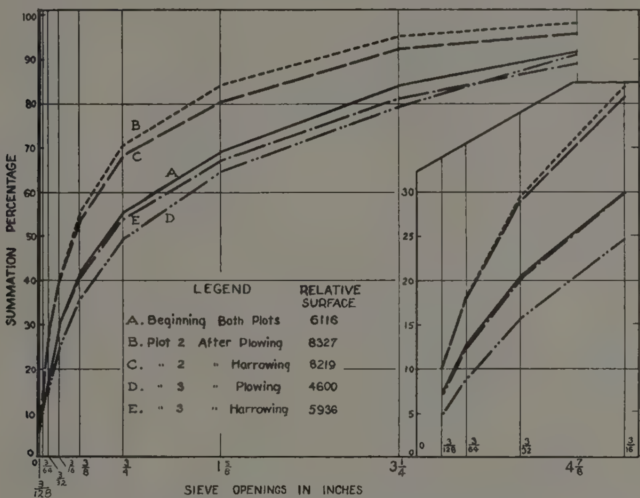

Fig. 11.—Size distribution of aggregates before and after tillage operations on plots 2 and 3 on Yolo loam, 1933.

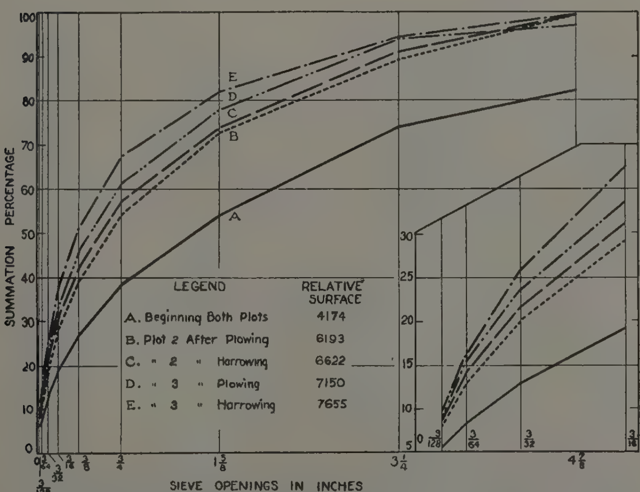

Fig. 12.—Size distribution of aggregates before and after tillage operations on plots 2 and 3 on Yolo silt loam, 1933.

nounced on the plot (No. 3) plowed at the higher moisture content. In this instance, however, although the furrow slice coming off the plowshare had a very slick shiny surface, the soil was not wet enough to prevent the soil from scouring off the plowshare.

Harrowing on these two plots seems to have had only a slight pulverizing effect. In both cases the curve for the harrowing treatment is slightly above that for plowing. There is some increase in the relative-surface values and, as shown on the enlargement of the lower end of the curves, some increase in the finer fractions.

In 1934 on Yolo loam (fig. 13), the plot that had been plowed too wet the year before was more cloddy before plowing than the one that had been plowed at a favorable moisture content. Plowing had a very definite pulverizing effect on both plots. The pulverizing effect on the wet plot was slightly greater than that on the drier one. The curves (*B* and *E*) for the plots after plowing fall closer together than those (*A* and *D*) for the plots before plowing. The numerical increases in the relative-surface values are similar for the two plots: the increase on the drier plot was from 4,718 to 7,186, an increase of 2,468; and on the wet plot from 2,936 to 5,463, an increase of 2,527.

Harrowing had a pulverizing effect on both areas (curves *C* and *F*). Here again, the amount of pulverizing on the wet plot exceeds that on the drier plot for this treatment. After both tillage operations, plot 2, the drier plot, was still in a slightly finer state of pulverization than plot 3.

For the same season, on Yolo silt loam (fig. 14), the curves (*A* and *D*) for the size distribution of aggregates before treatment fall very close together, yet there is considerable difference in the relative-surface values. Here again the large difference in this value is caused by the difference in the finest fraction. The curves are almost parallel, but curve *A* starts slightly above curve *D*.

Plowing had a distinct pulverizing effect on both plots, with a slightly greater effect on the drier plot, while harrowing had no pulverizing effect on the drier plot and only a very slight effect on the wet plot. After both tillage operations, the curve (*C*) for plot 2 is slightly higher than that (*F*) for plot 3, but the curves lie very close to each other throughout their length. The tillage operations seem to have had a very similar effect on both plots for this soil type.

In order to compare the results of treatments on the different soil types, the data were replotted. Figure 15 shows for the two soil types the results of tillage operations on the plots plowed at favorable moisture conditions in 1933.

The curves in figure 15 indicate that, when plowing was done at a

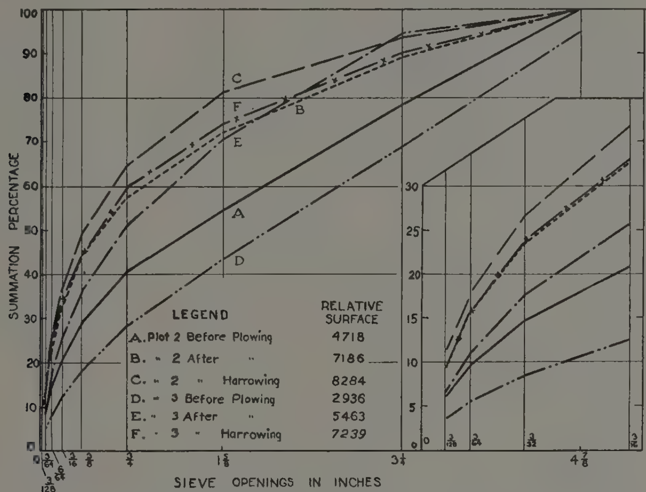

Fig. 13.—Size distribution of aggregates before and after tillage operations on plots 2 and 3 on Yolo loam, 1934.

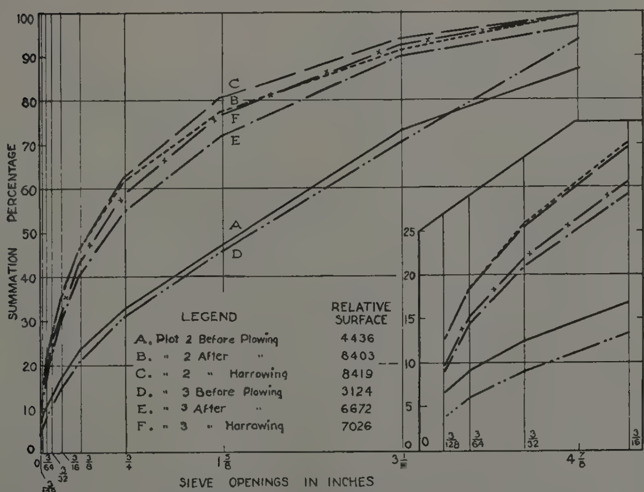

Fig. 14.—Size distribution of aggregates before and after tillage operations on plots 2 and 3 on Yolo silt loam, 1934.

favorable moisture content, the effects of tillage operations were very similar on the two soil types. The Yolo silt loam was more cloddy before any tillage and also more cloddy after the tillage. On both types, the curves for the plowing and harrowing are very close together, although on the Yolo silt loam the relative-surface value after plowing is slightly

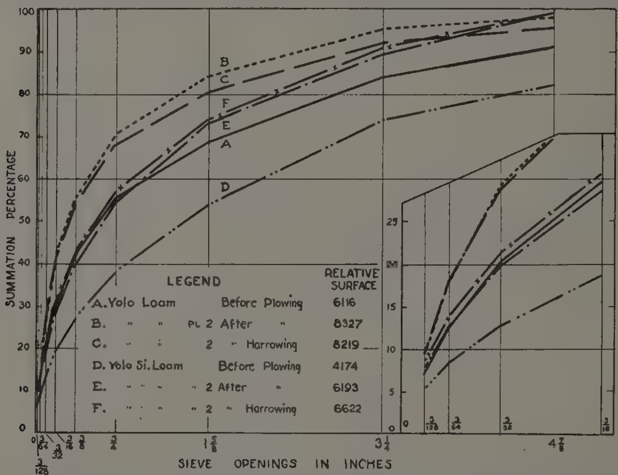

Fig. 15.—Size distribution of aggregates before and after tillage operations on plot 2 of both Yolo loam and Yolo silt loam, 1933. (Curves *A* and *D* from plot 1).

lower than after harrowing; on the Yolo loam, the relative-surface values for the two treatments are almost identical.

Similar graphs were made for plot 2 for 1934 and for plot 3 for each year, but since this constitutes merely a regrouping of the curves already given in figures 11, 12, 13, and 14, these graphs are omitted.

A comparison of curves *A, B,* and *C* on figures 13 and 14, shows that on plot 2 for 1934 on both soils, there was a stronger pulverizing effect on the silt loam, although both plots showed a very definite decrease in cloddiness. Harrowing in this year had a distinct pulverizing effect on the loam but no effect on the silt loam. After the tillage operations, these two soils were in very much the same condition (curve *C,* figs. 13 and 14).

With the plots plowed at high moisture contents, there was in 1933 a strong contrast in the effect of plowing. Before plowing, the Yolo loam was less cloddy than the silt loam (curve *A,* figs. 11 and 12), but the plowing increased the cloddiness on the loam plot and decreased it on the silt loam (curve *D,* figs. 11 and 12), so that after plowing the condi-

tion of the two plots was just reversed. Harrowing had a definite pulverizing effect on the loam and only a slight pulverizing effect on the silt loam. At the end of the tillage operations the former was nearly the same as it was originally, whereas the latter was much less cloddy.

Next year both plots that had been plowed too wet were in about the same condition before plowing, but materially more cloddy than they were the previous year. The plowing greatly reduced the cloddiness on both plots (curves *D* and *E*, figs. 13 and 14) but especially on the silt loam. The harrowing had only a slight effect on both plots (curve *F*, figs. 13 and 14) but was slightly more effective in pulverizing the loam plot, so that after the tillage operations, both plots were again very similar but much less cloddy than they had been before the tillage operations.

EFFECT OF IRRIGATION ON SIZE DISTRIBUTION OF AGGREGATES

The same two areas were sampled after some of the series of irrigations, and the size distribution of the aggregates after the irrigation may be compared with that before irrigation. The irrigation water was applied in basins to depths of about 6 inches at each application. On these plots there were from 3 to 5 applications of water, usually only a day or two apart. Figures 16 and 17 give the curves for the size distribution of aggregates for the Yolo loam and Yolo silt loam plots for 1933. In all cases there was some increase in cloddiness after the irrigation.

On the Yolo loam (fig. 16), a great increase in cloddiness occurred on the untilled check plot (No. 1) and on plot 2, which was plowed at a favorable moisture content. On plot 3, plowed too wet, there was only a slight change in the relative-surface value, yet the curves (*E* and *F*) are rather well separated in the upper half. They are, however, very close for the three finest fractions, which have the greatest influence on the relative-surface value. The peculiar behavior of this plot is further reflected in the slightness of its change after the irrigation treatment as compared to the other two plots sampled at the same period.

On the untilled Yolo silt loam, according to the curves (fig. 17, curves *A* and *B*), a considerable increase in the cloddiness was caused by irrigation. But this difference is not reflected in the relative-surface values for these two treatments: there is a slight difference, showing possibly a slight increase in cloddiness, but not nearly so much as one would expect from the comparison of the two curves. The slightly greater amount of the two finest fractions after the irrigation treatment accounts for this. Irrigation of the two plots that had been tilled caused an increase in the cloddiness. The increase was far greater, however, in the plot plowed too

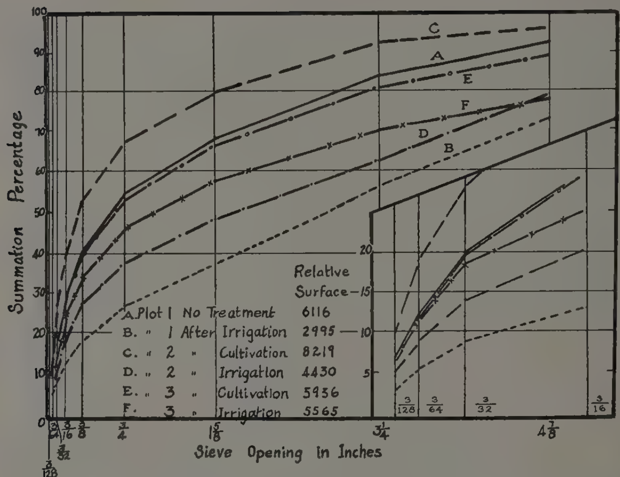

Fig. 16.—Size distribution of aggregates before and after irrigation on all three plots on Yolo loam, 1933.

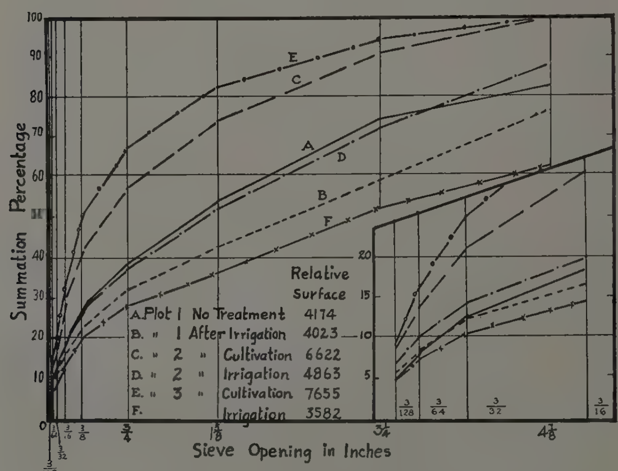

Fig. 17.—Size distribution of aggregates before and after irrigation on all three plots on Yolo silt loam, 1933.

wet (curves E and F) than in the one plowed under favorable moisture conditions (curves C and D). On these two plots, the differences in both the curves and the relative-surface value are pronounced.

Figures 18 and 19 show the results of similar treatments on the same two soil types for 1934. On the Yolo loam during this season there was a definite increase in cloddiness after the irrigation treatments on each of the plots. The change was not so pronounced for this year as it had been the previous year for the plot receiving no tillage operations. The plot plowed too wet showed a greater increase in cloddiness this season than it had the season before, whereas the plot plowed under favorable moisture conditions behaved about the same during the two seasons.

On the Yolo silt loam (fig. 19), the untilled plot showed no difference in its condition before and after the irrigation treatment and, in fact, not much difference from its condition at the beginning of these investigations in 1933. The relative-surface values before any treatments and after the irrigation treatments in 1934 are very close. There was a great increase in the cloddiness after irrigation on the other two plots on this same soil. On the plot plowed under favorable moisture conditions, the increase for this season was far greater than was the case for the previous season, whereas the behavior of the plot plowed too wet was very similar for both seasons.

After the tillage operations on each series of plots in 1933, the plots were all irrigated, then planted to barley. During the summer, two more series of irrigations were made, the last one near the end of July. The plots were permitted to remain untouched thereafter until early in December, when they were again sampled. The results are given in figures 20 and 21. There does not appear to be any consistent order of change. Some of the plots are more cloddy and some are less cloddy than at the previous sampling period.

The results on the Yolo loam (fig. 20) show a much less cloddy condition for plot 1 at the later sampling period. Curves A and B are wide apart and the relative-surface values are 2,995 and 5,728, respectively. The plot plowed at a favorable moisture content was only slightly altered (curves C and D), whereas the plot plowed at a very high moisture content was somewhat cloddier at the end of the season.

The variability between plots is not nearly so great on the Yolo silt loam (fig. 21). On this soil there was little or no difference in the aggregate condition of plot 1 at the beginning and end of the season according to the curves (A and B), and only a very slight difference according to the relative-surface values. Plot 2 was somewhat more cloddy at the later sampling period and plot 3 much less so.

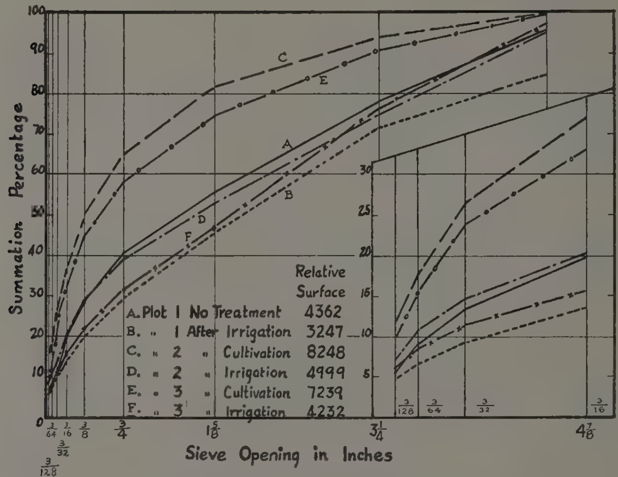

Fig. 18.—Size distribution of aggregates before and after irrigation on all three plots on Yolo loam, 1934.

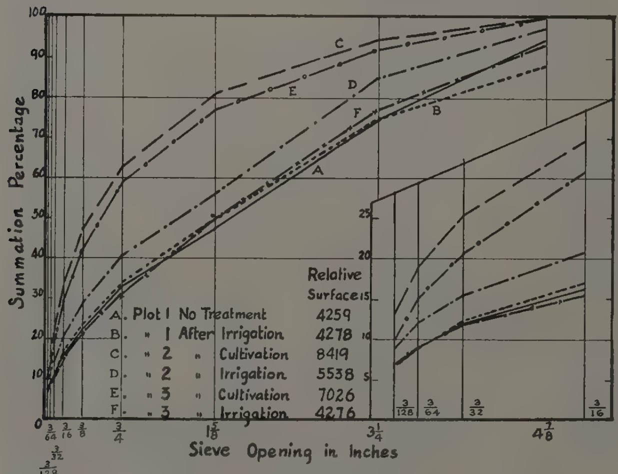

Fig. 19.—Size distribution of aggregates before and after irrigation on all three plots on Yolo silt loam, 1934.

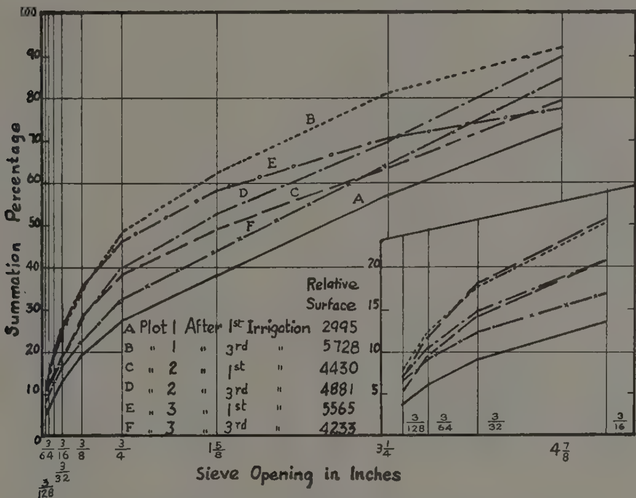

Fig. 20.—Size distribution of aggregates after the first and third irrigations on all three plots on Yolo loam, 1933.

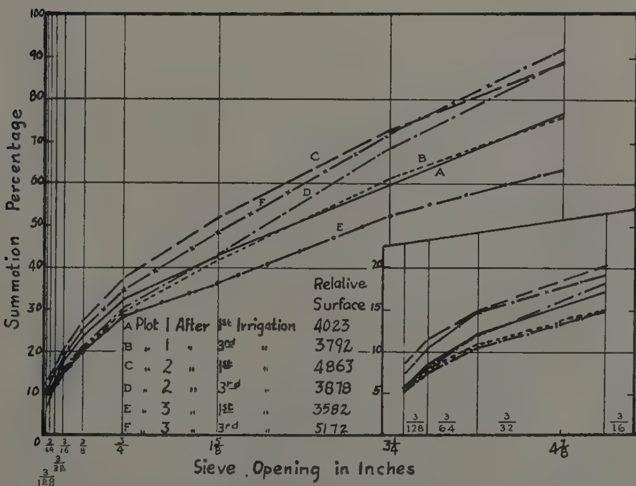

Fig. 21.—Size distribution of aggregates after the first and third irrigations on all three plots on Yolo silt loam, 1933.

The results on the two soils are directly contrasting: where there was a strong decrease in the cloddiness in plot 1 of the Yolo loam, there was practically no change for the same plot on the Yolo silt loam. On plot 2 of the Yolo loam there was a slight decrease in cloddiness and a rather definite increase on the Yolo silt loam. On plot 3 there was a definite increase in cloddiness on the Yolo loam and a slightly greater decrease on the Yolo silt loam. There does not seem to be any satisfactory explanation for the consistent contrast between these two soils in their responses to repeated irrigations. The results of the tillage operations already given were fairly consistent for both of these soils.

The effect of irrigation after tillage on the Yolo clay loam and Capay adobe clay, where the fields were being prepared for seedbed, has already been mentioned (figs. 3 and 4, p. 445). In both of these instances, as was the case with nearly all others, irrigation following cultivation caused an increase in cloddiness of the soil, so that the field, after irrigation, was more cloddy than before it was tilled.

SEASONAL VARIATIONS

The variation of the size distribution of aggregates from season to season is often as great as changes brought about by tillage operations or application of irrigation water. The seasonal changes were observed on the series of plots on Yolo loam and Yolo silt loam described in the preceding section.

In the spring of 1934 all plots were irrigated before the samples were taken, so that the changes occurring in the size distribution of aggregates over the winter period were not determined. The results for the period between the last sampling in 1934 and the first sampling in 1935 are given in figures 22, 23, and 24. In all plots on both soil types, the soils are more cloddy in the spring than they were the previous fall. The changes are greater on the Yolo silt loam than on the Yolo loam. On plots 1 and 2 (figs. 22 and 23) at the last sampling in 1934, the Yolo loam was somewhat coarser than the Yolo silt loam, and on plot 3 (fig. 24), the two soils had about the same size distribution of aggregates. When samplings were taken the following spring, plot 1 on the Yolo loam, according to its relative-surface value, was slightly coarser than the same plot on the Yolo silt loam, although, except for a short distance at the finer end, the curve (B) of size distribution for Yolo loam lies above that (D) for Yolo silt loam. On the other two plots, the Yolo silt loam is slightly coarser than the Yolo loam.

There is a great increase in the cloddiness of all plots at the conclusion of the sampling period in the spring of 1935 over that at the beginning

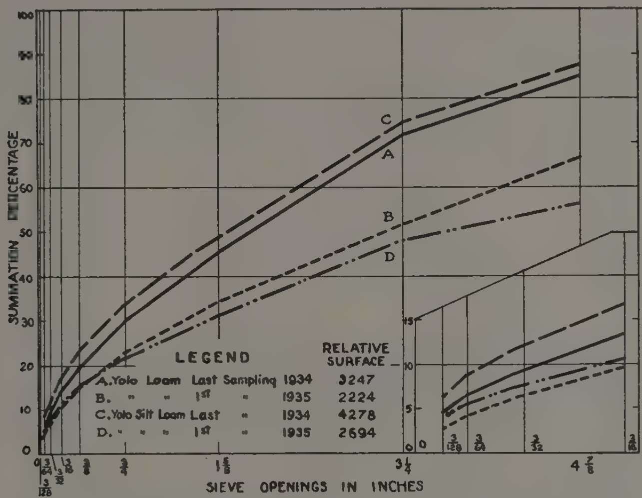

Fig. 22.—Changes in size distribution of aggregates on plot 1 of Yolo-loam and Yolo-silt-loam areas during the winter 1934–35.

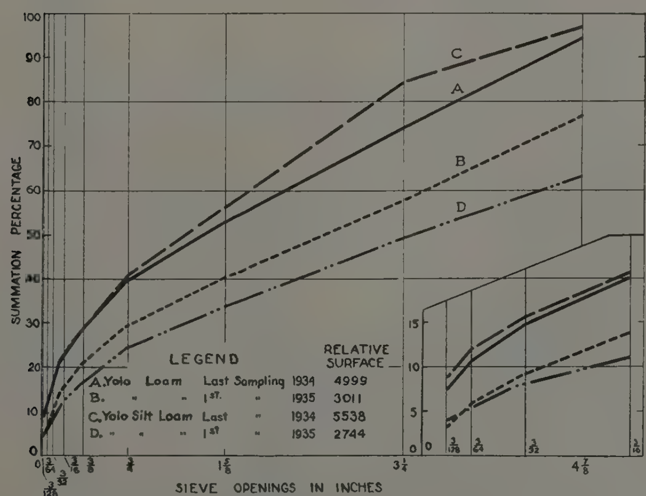

Fig. 23.—Changes in size distribution of aggregates on plot 2 of Yolo-loam and Yolo-silt-loam areas during the winter 1934–35.

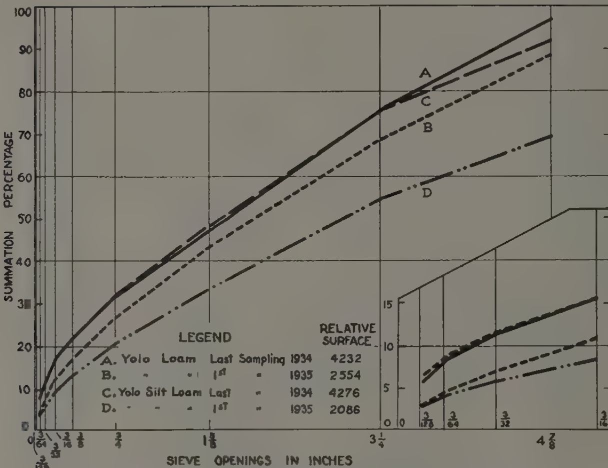

Fig. 24.—Changes in size distribution of aggregates on plot 3 of Yolo-loam and Yolo-silt-loam areas during the winter 1934–35.

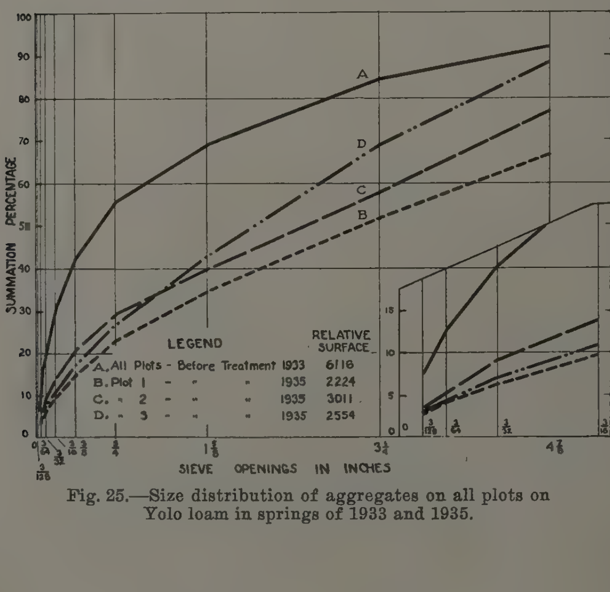

Fig. 25.—Size distribution of aggregates on all plots on Yolo loam in springs of 1933 and 1935.

of the experiment in 1933. The data for these sampling periods are plotted in figures 25 and 26. The tillage operations did not have a lasting effect on the size distribution of aggregates on either soil; for the untilled plots had as much change as did the tilled plots. In fact, in 1935 on the Yolo loam, the untilled plot had the lowest relative-surface value of the

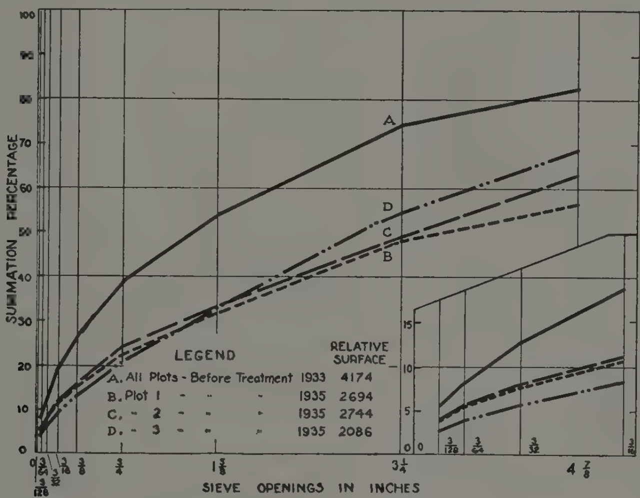

Fig. 26.—Size distribution of aggregates on all plots on Yolo silt loam in springs of 1933 and 1935.

three plots, whereas on the Yolo silt loam, the plot plowed too wet had the lowest value.

The seasonal changes over the winter period in the vicinity of Davis are somewhat similar to those obtained by irrigation treatments. This is not surprising because the winters at Davis are mild, the soils never freeze, and nearly all of the season's total rainfall of about 17 inches comes in a five-month period from December to May. The surface soils are usually wet to field capacity after the first few rains and remain so until the end of the rainy season, with seldom an opportunity for drying out.

DISCUSSION

From the data presented, and the rather consistent general tendencies observed, the air-dry sifting used throughout this work appears to give a better picture of the size distribution of aggregates in the field than when the samples are sifted moist, despite the fact that the replicate samplings are equally variable by either method. The aggregates in the

moist condition are so weak that the mechanical action necessary for a good separation into the respective sizes is sufficient to break down some of them, so that the resultant data do not give an accurate picture of the size distribution at the time of sampling.

It is fairly certain that the method of sifting in the air-dry condition gives a good picture of size distribution just before sifting, but the question still arises as to whether or not the samples when air-dry and ready for sifting had the same condition of aggregation as that when in the field prior to sampling. The method of sampling being uniform, the change, if any, in the size distribution of aggregates must be very small because of the care with which the samples were taken. If a change in the size distribution of aggregates is brought about by air-drying the samples, then a further question arises as to how much difference there is in the size distribution of aggregates when the sample is dried in the boxes, as was the case in this work, and when drying takes place naturally in the field. These questions need further study, but at present it seems that the changes that take place during the drying process were not very great, and probably much smaller than the natural differences due to heterogeneity of the soil, so that the measurements of aggregates in the air-dry condition give a good picture of the size distribution of aggregates at the time the samples were taken.

The number of tillage operations used in preparing a seedbed is often more a matter of habitual practice than a careful consideration of the physical condition to be attained for the particular crop. Year after year, many farmers use the same tillage operations, irrespective of the physical condition of the soil. Under such practices, undoubtedly many tillage operations are performed that are wholly unnecessary. The farmer may just as well be saved the cost of performing such operations by a more careful observation of the condition of the field and the condition required for the use to which the field is to be put.

A consideration of the curves showing changes in size distribution of aggregates in preparing seedbeds shows that in a number of instances, the size distribution of the aggregates at the final fitting of the field for seeding was not greatly different from that before any tillage operations were performed. A rather striking example of such a condition is shown in the area of Yolo clay loam prepared as a seedbed for beans (fig. 3, curves *A* and *F*, p. 445), in which the size distribution of aggregates is almost identical before any tillage operations and after the final tillage operation.

It is a common practice, when beans and other late-planted crops are grown under irrigation, to plow and harrow, then irrigate before final

fitting for the seedbed. In view of the information regarding the effect of irrigation following tillage operations, it seems that in many instances, at least one tillage operation may be eliminated by applying water before plowing, or at least immediately after plowing, rather than after harrowing, provided the field does not need leveling, which should always be done when the soil is fairly dry.

Because of the great influence of irrigation water in increasing the cloddiness of soils that are finely pulverized, a field soon to be irrigated should not be worked down too fine. A similar rule should be followed for fields to be left over the winter. If the field is worked up too fine, the first rains will pack and puddle the surface, and prevent later rains from penetrating so easily. Not only may this cause the removal of some of the rain water that otherwise would have been absorbed, but also the runoff may cause damage by erosion. It is especially important that fall-sown crops, fallow land, and cultivated permanent crops be left loose and open and somewhat cloddy at the beginning of the rainy season. This, of course, applies only to medium- or heavy-textured soils. Leaving light-textured soils worked up too loose may cause damage by wind movement.

In all cases where irrigation water was applied after tillage, the soil was much more cloddy than before irrigation, and in many cases it was more cloddy than before tillage. In fact, in more than half of the instances here recorded, the greater the state of pulverization before irrigation, the coarser the condition after irrigation. All irrigations considered in this work were of the basin type, where the whole surface was covered with water.

These findings would indicate that where areas are to be irrigated during the summer by the basin method—which is a common practice in deciduous orchards in the flatter valley lands of California—it is not necessary to cultivate to a fine mulch before irrigation, for this will nullify all of the pulverizing effect of tillage. Since a mulching does not conserve the field moisture by reducing evaporation where the water table is more than 6 feet from the surface (*17*, *19*), it seems that the only reason for cultivating in orchards under the above conditions would be for the purpose of controlling weeds, or turning under covercrops, or putting the surface soil in a condition to reduce the loss of moisture by runoff during the rainy season.

The samples from untilled plots of the Yolo loam and Yolo silt loam soils indicate that the seasonal changes in the size distribution of aggregates are great, and that the wetting of the soil, both by winter rains and by irrigation water, brings about changes in the size distribution of aggregates that are often as great as changes brought about by tillage implements.

SUMMARY

The present study offers a method of measuring quantitatively changes in the size distribution of aggregates and the volume weight of the soil.

Three factors which are important in these changes are tillage, irrigation, and winter rains. In general, the results of these factors are as follows:

1. Plowing caused a decrease in cloddiness and volume weight unless performed at excessive moisture contents.

2. Harrowing usually did some breaking up of clods. Disk and spring-tooth harrows seemed more effective than spike-tooth harrows in reducing cloddiness.

3. Rolling and leveling operations increased the volume weight and had a pulverizing effect on the very dry soils, but moderately moist soils usually showed increased cloddiness after these operations.

4. The cloddiness of soils worked up to a fine, highly pulverized condition was greatly increased by irrigation, often to a point far in excess of that before any tillage. Tilled areas that were left cloddy showed some increase in cloddiness, but not so much as those that had been highly pulverized.

5. Winter rains often have as great an influence on the size distribution of aggregates as the tillage operations or irrigations.

A general view of the data presented shows that even under fairly well controlled conditions, the results obtained by any one cultural treatment are not always the same, but fairly comparable. The differences may be due to the natural heterogeneity of the soil or to factors that could not be readily observed.

This method offers a good means of studying the effects of various tillage implements in pulverizing the soil, and from these studies, it should be possible to determine the most efficient method of preparing the soil for any desired use. Other important relations, such as seasonal changes and changes due to irrigation and subsequent drying, may be studied, which should lead to a more efficient use of irrigation water and tillage implements.

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